RUMINANT NUTRITION SYMPOSIUM: Productivity, digestion, and health responses to hindgut acidosis in ruminants

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ABSTRACT: Microbial fermentation of carbohydrates in the hindgut of dairy cattle is responsible for 5 to 10% of total-tract carbohydrate digestion. When dietary, animal, or environmental factors contribute to abnormal, excessive flow of fermentable carbohydrates from the small intestine, hindgut acidosis can occur. Hindgut acidosis is characterized by increased rates of production of short-chain fatty acids including lactic acid, decreased digesta pH, and damage to gut epithelium as evidenced by the appearance of mucin casts in feces. Hindgut acidosis is more likely to occur in high-producing animals fed diets with relatively greater proportions of grains and lesser proportions of forage. In these animals, ruminal acidosis and poor selective retention of fermentable carbohydrates by the rumen will increase carbohydrate flow to the hindgut. In more severe situations, hindgut acidosis is characterized by an inflammatory response; the resulting breach of the barrier between animal and digesta may contribute to laminitis and other disorders. In a research setting, effects of increased hindgut fermentation have been evaluated using pulse-dose or continuous abomasal infusions of varying amounts of fermentable carbohydrates. Continuous small-dose abomasal infusions of 1 kg/d of pectin or fructans into lactating cows resulted in decreased diet digestibility and decreased milk fat percentage without affecting fecal pH or VFA concentrations. The decreased diet digestibility likely resulted from increased bulk in the digestive tract or from increased digesta passage rate, reducing exposure of the digesta to intestinal enzymes and epithelial absorptive surfaces. The same mechanism is proposed to explain the decreased milk fat percentage because only milk concentrations of long-chain fatty acids were decreased. Pulse-dose abomasal fructan infusions (1 g/kg of BW) into steers resulted in watery feces, decreased fecal pH, and increased fecal VFA concentrations, without causing an inflammatory response. Daily 12-h abomasal infusions of a large dose of starch (~4 kg/d) have also induced hindgut acidosis as indicated by decreased fecal pH and watery feces. On the farm, watery or foamy feces or presence of mucin casts in feces may indicate hindgut acidosis. In summary, hindgut acidosis occurs because of relatively high rates of large intestinal fermentation, likely due to digestive dysfunction in other parts of the gut. A better understanding of the relationship of this disorder to other animal health disorders is needed.

Key words: acidosis, hindgut, ruminant

INTRODUCTION

The role of large intestinal or hindgut fermentation in ruminant nutrition has received little research attention in recent decades. Although the contribution of the hindgut to total-tract nutrient digestion is substantially less than the contribution from the rumen, hindgut fermentation affects animal production and health. As described subsequently, hindgut fermentation typically provides 5 to 10% of dietary energy but certain conditions such as ruminal acidosis can lead to excessive carbohydrate fermentation in the hindgut. Hindgut acidosis can be defined as an accumulation of organic acids and a subsequent decrease in digesta pH and dramatic shifts in microbial populations that may cause damage to the animal; it is often indicative of failure of healthy ruminal function. Risk of hindgut acidosis likely increases with production level and fermentable carbohydrate intake, but previous reviews have focused...
primarily on animals fed near maintenance. The first part of this review describes normal aspects of hindgut fermentation with a focus on lactating cows. The second part of this review describes conditions that lead to excessive hindgut fermentation with its consequences for production and health. This review focuses primarily on cattle because most of our current understanding of the consequences of hindgut acidosis in ruminants has been derived from cattle studies.

WHAT IS NORMAL?

Hindgut Anatomy and Microbial Fermentation

In this review, the hindgut is defined as the large intestine, which consists of the cecum, colon, and rectum. In cattle, the lack of a distinct anatomical division between the cecum and colon results in similar fermentation profiles in both locations (Elsden et al., 1946). The wet digesta in the hindgut of the cow accounts for approximately 2% of BW compared with approximately 13% for horses (Engelhardt and Rechtemmer, 1983) and 14% for the rumen of a cow (Dado and Allen, 1995). The differences in volume indicate that the hindgut has about 14% of the capacity for fermentation of the rumen. However, particle retention time in the hindgut is considerably less than that in the rumen (i.e., 13 vs. 30 h; Vanhatalo and Ketoja, 1995; Yang et al., 2002), which may reduce the extent of substrate fermentation in the hindgut versus the rumen. Substrates entering the hindgut are also generally less digestible than those in the rumen because they have already been acted upon by rumen bacterial enzymes and small intestinal enzymes. Consequently, the actual proportion of fermentation in the hindgut compared with the rumen may sometimes be less than expected by volume comparison, although that is not always the case. For example, starch disappearance as a fraction of the amount entering has sometimes been found to be greater in the hindgut than the rumen (Ali Haïmoud et al., 1995; Callison et al., 2001). Additionally, NDF digestibility is sometimes found to be greater in the hindgut than in the rumen, particularly as dietary concentrations of nonforage fiber sources increase (Firkins, 1997).

Bacteria in both the rumen and hindgut possess cellular, protease, deaminase, and urease activities, and products of fermentation include VFA, NH₃, and microbial cells (Nolan, 1975; Stevens et al., 1980). Digesta in both compartments have similar reduction potentials, oxygen tensions, and pH (Stevens et al., 1980; McNeil, 1988; Hume, 1997), and fat digestion is negligible (Ulyatt and MacRae, 1974). Methane is also produced in both locations and the hindgut is responsible for 6 to 14% of CH₄ output by cattle (Imming, 1996). Bacterial concentrations are similar at 10¹⁰ to 10¹²/ml, with greater than 95% anaerobes (McNeil, 1988; Hume, 1997). The rumen and hindgut both contain distinct populations of bacteria including luminal bacteria and epithelium-associated bacteria; however, mucus-associated bacteria are an additional population in the hindgut (Hume, 1997).

Carbohydrates are fermented to VFA and gas at similar rates in the rumen and hindgut (McNeil, 1988; Hume, 1997; Váradyová et al., 2000). Volatile fatty acid profiles in both locations respond similarly to changes in substrates; for example, the ratio of acetate to propionate increases in both locations in response to increased NDF fermentation, whereas it decreases in response to increased starch fermentation (Orskov et al., 1970; Hoover, 1978; Siciliano-Jones and Murphy, 1989; Hume, 1997). The majority (>95%) of VFA produced in the hindgut are passively absorbed across the intestinal epithelium (Argenzio et al., 1975; Engelhardt and Rechtemmer, 1983). Absorbed butyrate is largely metabolized for energy by the ruminal mucosa and the same is believed to be true for the hindgut (McNeil, 1988), although an in vitro study of sheep cecal and ruminal mucosa found that the rumen slices predominantly metabolized butyrate, whereas the cecum slices predominantly metabolized acetate (Packett et al., 1966). The hindgut was found to account for 8 to 17% of total VFA absorbed from the digestive tract of ruminants (Hoover, 1978; McNeil, 1988), supplying 5 to 12% of ME in steers (Váradyová et al., 2000), 5% of DE intake in sheep (Faichney, 1968), and 10% of total tract GE disappearance in sheep (Beever et al., 1972). As is the case in the rumen, the fractional rate of VFA absorption across the cecum increases with decreasing pH (Myers et al., 1967; Dijkstra et al., 1993).

Differences in buffering capacity and gut epithelium between the rumen and hindgut may make the hindgut less capable of maintaining digesta pH during times of increased VFA production. Bicarbonate passes across the epithelium into both the rumen and hindgut. However, saliva provides an additional bicarbonate supply to buffer the rumen, approximately 1 and 3 kg/d NaHCO₃ in nonlactating and lactating cattle, respectively (Erdman, 1988), and this does not occur in the hindgut. Protozoa are also absent in the hindgut of ruminants (Hume, 1997). In the rumen, protozoa sequester rapidly fermentable carbohydrates and slow the pH decline after a meal (Jouany et al., 1988). This natural defense against ruminal acidosis is therefore lacking in the hindgut. Additionally, Hume (1997) suggested that the mucus layer covering the intestinal mucosa results in a microclimate with a pH near 7 that is fairly unresponsive to changes in digesta pH. Therefore, decreasing digesta pH due to increasing VFA concentrations may be less able to stimulate increased VFA absorption rates in the hindgut than in the rumen. Some absorption of VFA from the rumen is bicarbonate-dependent, leading to transfer of bicarbonate to the lumen (Penner et al., 2009). If similar bicarbonate-dependent VFA absorption occurs in the hindgut, failure of decreased digesta pH to increase VFA absorption rate in the hindgut would decrease bicarbonate transfer to the hindgut. Finally,
differences in gut epithelium structure likely make the hindgut epithelium more susceptible to organic acid-induced damage than the rumen. Unlike the large intestinal mucosa, ruminal epithelium has a stratum corneum layer. The stratum corneum, a layer of dead keratinized cells, serves as a permeability and antimicrobial barrier (Elias, 2005). With a relatively lesser ability to buffer digesta and lack of a specifically protective layer of the epithelium, compromise of the mucus layer would leave the large intestinal mucosa open to destruction by microbes and their products. For example, acetic acid (0.1 M) showed a time- and pH-dependent ability to damage colonic epithelium in the pig (Argenzio and Meuten, 1991). The damage included subepithelial blistering, sloughing of the surface epithelium, and increased permeability; damage was greater than that caused by acidified NaCl at the same pH. In summary, the hindgut is a fermentation compartment with less buffering capacity than the rumen. It functions to allow additional digestion of feed and harvest of nutrients not accomplished previously in the gut.

**Contribution of the Hindgut to Total-Tract OM and Carbohydrate Disappearance**

Animals with cannulas in the terminal ileum can be used to determine the proportion of digestion that occurs in the hindgut. Tables 1, 2, and 3 summarize flows of OM, nonstructural carbohydrates (NSC), and structural carbohydrates, respectively, in steers, sheep, and lactating cows fitted with duodenal and ileal cannulas. Results presented are the means calculated from all treatments presented in each reference. The final column of each table contains the contribution of the hindgut to substrate disappearance calculated as a percentage of total-tract substrate disappearance. The range, mean, and median, respectively, are –13.0 to 22.2%, 6.7%, and 7.0% for OM; 0.0 to 11.7%, 4.5%, and 4.6% for starch; –4.6 to 14.1%, 5.5%, and 7.0% for NSC; and 3.7 to 23.2%, 11.9%, and 11.1% for NDF. Acid detergent fiber and cellulose were each evaluated in only 2 studies, and large intestinal contribution to total-tract disappearance averaged 4.9% for ADF in cows and 12.1% for cellulose in sheep.

The degree to which fermentation occurs in the hindgut of dairy cows is approximately equal to, if not greater than, substrate fermentation in the hindgut of steers. For OM, an average of 0.69 (13%) of the 5.32 kg of OM that entered the ileum disappeared between the ileum and feces in lactating cows (Table 1). These numbers were 0.27 (15%) of 1.77 kg of ileal OM in steers. However, 258 (54%) of 474 g of ileal starch disappeared in the hindgut of lactating cows, whereas 87 (28%) of 307 g of ileal starch disappeared in the hindgut of steers (Table 2). Therefore, the hindgut accounted for an average of 5.4% (range = 0.4 to 11.7%) of total-tract starch disappearance in lactating cows and 2.9% (range = 0.0 to 6.8%) in steers on the diets evaluated. The potential for starch to induce hindgut acidosis is likely a function of total mass delivered to that gut compartment and its rate of fermentation. In both cows and steers, when flow of starch to the ileum was low (i.e., 0 to 110 g/d), the contribution of the hindgut to total-tract starch disappearance was small (i.e., 0.0 to 2.0%).
When flow of starch to the ileum was greater (i.e., 340 to 1,650 g/d), the contribution of the hindgut to total-tract starch disappearance was also greater (i.e., 4.6 to 11.7%). Greater rates of passage in high-producing animals generally reduce ruminal starch digestibility and may increase risk of hindgut acidosis in cows compared with steers.

In his review, Firkins (1997) found that an average of 34% of total-tract NDF digestion in duodenally cannulated lactating dairy cows occurred postruminally, presumably in the large intestine. This is greater than the 11.9% average for the studies presented in Table 3, although Firkins (1997) did indicate that substantial variation existed among studies despite having all been done by the same laboratory using traditional feedstuffs. Huhtanen et al. (2010) conducted a meta-analysis on 32 trials from 5 research groups that used omasal sampling to determine rumen NDF disappearance. Similar to the data from this review, they found that 5% of total-tract NDF digestion occurred postruminally. They also indicated that the omasal sampling and triple marker technique led to substantially less residual variation than studies using duodenally cannulated cows (Huhtanen et al., 2010). Firkins (1997) also

### Table 2. Starch and nonstructural carbohydrate disappearance in the digestive tract of steers, sheep, and lactating cows with duodenal and ileal cannulas

<table>
<thead>
<tr>
<th>Study</th>
<th>Animal</th>
<th>Intake, kg/d</th>
<th>Duodenal flow, kg/d</th>
<th>Ileal flow, kg/d</th>
<th>Fecal flow, kg/d</th>
<th>Fecal ileal, kg/d</th>
<th>Digestion in LI, % of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhao et al., 1996a</td>
<td>Steers</td>
<td>1.1</td>
<td>0.06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>Jensen et al., 2005</td>
<td>Cows</td>
<td>3.1</td>
<td>0.28</td>
<td>0.05</td>
<td>0.04</td>
<td>0.01</td>
<td>0.4</td>
</tr>
<tr>
<td>Zhao et al., 1996b</td>
<td>Steers</td>
<td>0.87</td>
<td>0.08</td>
<td>0.006</td>
<td>0.001</td>
<td>0.004</td>
<td>0.5</td>
</tr>
<tr>
<td>Theurer et al., 1999</td>
<td>Steers</td>
<td>4.1</td>
<td>0.86</td>
<td>0.11</td>
<td>0.08</td>
<td>0.03</td>
<td>0.8</td>
</tr>
<tr>
<td>Palmquist et al., 1993</td>
<td>Cows</td>
<td>2.3</td>
<td>0.21</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
<td>1.2</td>
</tr>
<tr>
<td>Prestbekken and Harstad, 2001</td>
<td>Cows</td>
<td>4.3</td>
<td>0.48</td>
<td>0.11</td>
<td>0.03</td>
<td>0.08</td>
<td>2.0</td>
</tr>
<tr>
<td>Rémont et al., 2004</td>
<td>Cows</td>
<td>4.5</td>
<td>2.06</td>
<td>0.76</td>
<td>0.58</td>
<td>0.18</td>
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</tr>
<tr>
<td>Ali Haimoud et al., 1995</td>
<td>Cows</td>
<td>5.4</td>
<td>2.23</td>
<td>0.47</td>
<td>0.13</td>
<td>0.33</td>
<td>6.3</td>
</tr>
<tr>
<td>Streeter et al., 1991</td>
<td>Steers</td>
<td>3.7</td>
<td>1.11</td>
<td>0.87</td>
<td>0.70</td>
<td>0.20</td>
<td>6.6</td>
</tr>
<tr>
<td>Streeter et al., 1995</td>
<td>Steers</td>
<td>3.3</td>
<td>0.96</td>
<td>0.55</td>
<td>0.35</td>
<td>0.20</td>
<td>6.8</td>
</tr>
<tr>
<td>Hindle et al., 2005</td>
<td>Cows</td>
<td>3.7</td>
<td>0.64</td>
<td>0.34</td>
<td>0.06</td>
<td>0.28</td>
<td>7.7</td>
</tr>
<tr>
<td>Fernandez et al., 2004</td>
<td>Cows</td>
<td>3.8</td>
<td>0.81</td>
<td>0.37</td>
<td>0.14</td>
<td>0.35</td>
<td>9.6</td>
</tr>
<tr>
<td>Knowlton et al., 1998</td>
<td>Cows</td>
<td>8.2</td>
<td>2.08</td>
<td>1.65</td>
<td>0.85</td>
<td>0.80</td>
<td>11.7</td>
</tr>
</tbody>
</table>

**Nonstructural carbohydrates**

<table>
<thead>
<tr>
<th>Study</th>
<th>Animal</th>
<th>Intake, kg/d</th>
<th>Duodenal flow, kg/d</th>
<th>Ileal flow, kg/d</th>
<th>Fecal flow, kg/d</th>
<th>Fecal ileal, kg/d</th>
<th>Digestion in LI, % of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waltz et al., 1989</td>
<td>Cows</td>
<td>5.8</td>
<td>1.84</td>
<td>0.22</td>
<td>0.46</td>
<td>−0.24</td>
<td>−4.6</td>
</tr>
<tr>
<td>Arieli et al., 2001</td>
<td>Cows</td>
<td>6.5</td>
<td>2.65</td>
<td>0.55</td>
<td>0.55</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>Zhao et al., 1996b</td>
<td>Steers</td>
<td>3.0</td>
<td>0.51</td>
<td>0.40</td>
<td>0.20</td>
<td>0.20</td>
<td>7.0</td>
</tr>
<tr>
<td>Callison et al., 2001</td>
<td>Cows</td>
<td>5.1</td>
<td>2.71</td>
<td>0.83</td>
<td>0.35</td>
<td>0.52</td>
<td>11.2</td>
</tr>
<tr>
<td>Zhao et al., 1996a</td>
<td>Steers</td>
<td>1.9</td>
<td>0.73</td>
<td>0.58</td>
<td>0.35</td>
<td>0.22</td>
<td>14.1</td>
</tr>
</tbody>
</table>

1Large intestinal (LI) contribution to total-tract disappearance calculated as [(fecal flow − ileal flow)/(intake − fecal flow)] × 100%.

When flow of starch to the ileum was greater (i.e., 340 to 1,650 g/d), the contribution of the hindgut to total-tract starch disappearance was also greater (i.e., 4.6 to 11.7%). Greater rates of passage in high-producing animals generally reduce ruminal starch digestibility and may increase risk of hindgut acidosis in cows compared with steers.

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### Table 3. Structural carbohydrate disappearance in the digestive tract of steers, sheep, and lactating cows with duodenal and ileal cannulas

<table>
<thead>
<tr>
<th>Study</th>
<th>Animal</th>
<th>Intake, kg/d</th>
<th>Duodenal flow, kg/d</th>
<th>Ileal flow, kg/d</th>
<th>Fecal flow, kg/d</th>
<th>Fecal ileal, kg/d</th>
<th>Digestion in LI, % of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palmquist et al., 1993</td>
<td>Cows</td>
<td>4.7</td>
<td>1.6</td>
<td>1.5</td>
<td>1.4</td>
<td>0.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Pantoja et al., 1994</td>
<td>Cows</td>
<td>6.6</td>
<td>3.6</td>
<td>3.2</td>
<td>2.9</td>
<td>0.3</td>
<td>7.6</td>
</tr>
<tr>
<td>Jensen et al., 2005</td>
<td>Cows</td>
<td>5.6</td>
<td>2.6</td>
<td>3.0</td>
<td>2.8</td>
<td>0.3</td>
<td>9.2</td>
</tr>
<tr>
<td>Callison et al., 2001</td>
<td>Cows</td>
<td>5.8</td>
<td>2.9</td>
<td>2.5</td>
<td>2.0</td>
<td>0.5</td>
<td>12.9</td>
</tr>
<tr>
<td>Younker et al., 1998</td>
<td>Cows</td>
<td>5.9</td>
<td>3.3</td>
<td>3.2</td>
<td>2.7</td>
<td>0.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Prestbekken and Harstad, 2001</td>
<td>Cows</td>
<td>6.0</td>
<td>2.5</td>
<td>3.3</td>
<td>2.5</td>
<td>0.8</td>
<td>23.2</td>
</tr>
</tbody>
</table>

**ADF**

<table>
<thead>
<tr>
<th>Study</th>
<th>Animal</th>
<th>Intake, kg/d</th>
<th>Duodenal flow, kg/d</th>
<th>Ileal flow, kg/d</th>
<th>Fecal flow, kg/d</th>
<th>Fecal ileal, kg/d</th>
<th>Digestion in LI, % of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palmquist et al., 1993</td>
<td>Cows</td>
<td>3.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.1</td>
<td>3.3</td>
</tr>
<tr>
<td>Kung et al., 1983</td>
<td>Cows</td>
<td>3.2</td>
<td>1.7</td>
<td>1.7</td>
<td>1.6</td>
<td>0.1</td>
<td>6.5</td>
</tr>
</tbody>
</table>

**Cellulose**

<table>
<thead>
<tr>
<th>Study</th>
<th>Animal</th>
<th>Intake, kg/d</th>
<th>Duodenal flow, kg/d</th>
<th>Ileal flow, kg/d</th>
<th>Fecal flow, kg/d</th>
<th>Fecal ileal, kg/d</th>
<th>Digestion in LI, % of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beever et al., 1972</td>
<td>Sheep</td>
<td>0.238</td>
<td>0.070</td>
<td>0.067</td>
<td>0.044</td>
<td>0.023</td>
<td>12.0</td>
</tr>
<tr>
<td>Ulyatt and MacRae, 1974</td>
<td>Sheep</td>
<td>0.116</td>
<td>0.023</td>
<td>0.025</td>
<td>0.012</td>
<td>0.013</td>
<td>12.2</td>
</tr>
</tbody>
</table>

1Large intestinal (LI) contribution to total-tract disappearance calculated as [(fecal flow − ileal flow)/(intake − fecal flow)] × 100%.
found that compensation occurred in the hindgut when ruminal NDF digestion was low. Treatment means from studies presented in Table 3 for hindgut NDF disappearance as a percentage of intake were plotted against ruminal NDF disappearance as a percentage of intake, and data and regression lines for each study are presented in Figure 1. To examine whether compensation for low ruminal NDF disappearance occurred in the hindgut, we conducted a simple mixed model meta-analysis examining the relationship between hindgut NDF disappearance and ruminal NDF disappearance (St-Pierre, 2001). The estimates of intercept and slope were 8.4 (SE = 5.5, \( P = 0.18 \)) and \(-0.03 \) (SE = 0.11, \( P = 0.82 \)), respectively, indicating that among those studies there was not compensation in the hindgut when ruminal NDF digestibility was low. Finally, for 4 of the 6 studies presented in Table 3, additional NDF loss occurred between the duodenum and ileum, indicating that some NDF fermentation may be taking place in the distal portion of the small intestine.

The summary of published data in Tables 1, 2, and 3 likely spans the range in hindgut digestion that can be expected in clinically healthy ruminants. The wide ranges indicate that, as with other biological systems, the hindgut has the ability to adapt to different loads without resulting in obvious stress to the animal. However, animals at the upper ends of the ranges in those studies might have experienced excessive hindgut fermentation. For example, the cows in the study by Knowlton et al. (1998) likely had abnormal rumen function, as indicated by low rumen NDF digestibility (i.e., 26 to 32%). This abnormal rumen function and subsequent increased flow of fermentable carbohydrates to the hindgut probably contributed to that study having the greatest large intestinal starch disappearance (Table 3). Conditions such as subacute ruminal acidosis (SARA) that increase postruminal flow of fermentable carbohydrates can cause increased hindgut fermentation (Hall, 2002; Plaizier et al., 2008). Prolonged or repeated exposure to acidic conditions in the hindgut may damage intestinal epithelium and have long-term consequences on animal health.

**WHAT IS NOT NORMAL?**

**Relationship Between Ruminal Acidosis and Hindgut Acidosis**

Ruminal acidosis occurs when rapid rates of carbohydrate fermentation and inadequate buffering or dietary fiber concentrations allow increases in ruminal concentrations of organic acids, leading to a decrease in ruminal pH. Acute acidosis and SARA are defined as occurring when ruminal pH is reduced below approximately 5.0 and 5.6, respectively, with precise pH definitions differing among groups (Krause and Oetzel, 2006; Penner et al., 2007; Radostits et al., 2007). In both types of acidosis, carbohydrates are rapidly fermented, rumen microbial populations shift, and ruminal organic acid concentrations increase, leading to a decline in ruminal pH (Krause and Oetzel, 2006; Plaizier et al., 2008; Khaifipour et al., 2009b). Acid accumulation and increased osmotic pressure of digesta can lead to damage and inflammation of the rumen epithelium and allow for systemic entry of endotoxins, bacteria, or amines that can cause inflammation or infection (Owens et al., 1998; Plaizier et al., 2008). Metabolic acidosis typically only occurs during acute acidosis; symptoms...
include decreased blood pH, increased heart rate, and increased respiratory rate, and if untreated can cause death (Owens et al., 1998; Krause and Oetzel, 2006). Symptoms common to both acute acidosis and SARA include decreased intake, decreased diet digestibility, localized and systemic inflammation, laminitis, lameness, reproductive failure, and decreased production (Oetzel, 2003; Krause and Oetzel, 2006; Plaizier et al., 2008). Gastroenteritis, an inflammation of the small intestine that may compromise its function, may also accompany ruminal acidosis (Sodhi et al., 1981).

Among cattle, feedlot steers and lactating dairy cows are at the greatest risk for developing ruminal acidosis because they are typically fed rations containing relatively greater proportions of grains and often lesser amounts of fiber and forages. Feeding diets with smaller particle size, such as diets low in forage and high in grain, can alter retention of feed particles in the rumen, resulting in increased flow of fermentable substrates to the hindgut (Van Soest, 1994). In fact, changes in fecal consistency in response to excessive hindgut fermentation, which include diarrhea, frothy feces, and presence of mucin casts, can be used in the field as indicators of SARA (Hall, 2002; Plaizier et al., 2008). Damage to large intestinal epithelium can also occur in association with ruminal acidosis (Thoefer et al., 2004). Equine models have demonstrated that excessive intestinal fermentation causes inflammation and laminitis, likely due to systemic entry of amines, endotoxins, or bacteria from a breach in the intestinal barrier (Crawford et al., 2007). Oetzel (2003) suggested that increased hindgut fermentation in cattle with SARA might cause similar damage to the intestinal lining and contribute to SARA symptoms. In support of this idea, Khaipour et al. (2009a) found that SARA induced by replacing alfalfa hay with ground alfalfa pellets caused similar changes in rumen pH, VFA, and lipopolysaccharide concentrations as found in SARA induced by increasing dietary grain. However, alfalfa pellet-induced SARA did not increase blood inflammatory markers as typically occurs during grain-induced SARA. They suggested that the inflammation that often accompanies SARA is due to systemic entry of endotoxins produced by intestinal bacteria as opposed to systemic entry of endotoxins produced by ruminal bacteria (Khaipour et al., 2009a). The destruction of colonic epithelium and development of mucin casts with application of organic acids in porcine models (Argenzio and Meuten, 1991) and increased fecal mucin excretion in humans consuming 20 g/d of fructooligosaccharides (Ten Bruggencate et al., 2006) support the concept that excessive amounts of intestinal fermentation can lead to postruminal signs noted for SARA.

Consequences of Excessive Hindgut Fermentation

Few studies have evaluated the effects of increased hindgut fermentation independent of ruminal acido-

sis. However, several studies in sheep have evaluated changes in fecal consistency in response to postruminal infusion of fermentable carbohydrates. Ileal infusions of up to 90 g of glucose decreased fecal DM percentage (Thornton et al., 1970), and cecal infusions of 300 g of starch increased fecal VFA concentration (Ørskov et al., 1970).

In cattle, results of postruminal starch infusions indicate that a considerable amount of starch can escape small intestinal digestion and be fermented in the hindgut. When lactating cows were infused abomasally with 0 or 1.2 kg/d of wheat starch, fecal pH was decreased from 6.64 to 6.26 with the starch infusion, indicating that some of the infused starch escaped small intestinal digestion and was fermented in the hindgut (Reynolds et al., 2001). Matthé et al. (2003) duodenally infused 0.9 or 1.8 kg/d of corn or wheat starch in nonlactating cows fed an all-forage diet and measured starch flow to the ileum and feces. At the low infusion level, 0.2 kg/d of starch reached the ileum and virtually none was excreted in the feces. At the greater infusion level, 0.8 kg/d of starch reached the ileum, 0.5 kg/d of that starch disappeared in the hindgut, and 0.3 kg/d was lost in the feces (Matthé et al., 2003). Finally, abomasal infusions of 4 kg/d of corn starch caused severe hindgut acidosis as evidenced by a decline in fecal pH from ~7 to <5, fecal excretion of mucin casts and tissue, and diarrhea (Bissell and Hall, 2010). In that study, responses of the starch-infused animals differed greatly, from animals apparently adapting with small intestinal digestion of the starch to those that did not and became gravely ill. Together, these studies indicate that starch is regularly fermented in the hindgut of cattle, and that the amount of starch that escapes small intestinal digestion has the potential to increase with increasing duodenal starch flow. Conditions such as ruminal acidosis that result in excessive duodenal starch flow and gastroenteritis that may compromise small intestinal function are likely to induce hindgut acidosis.

We have conducted 3 studies to evaluate effects of continuous abomasal infusions of 0 or 1 kg/d of pectin or oligofructose suspended in 10 to 30 L/d of saline in lactating dairy cattle (Gressley and Armentano, 2005, 2007). These neutral detergent soluble fibers (NDSF) are indigestible by mammalian enzymes but rapidly fermentable by bacteria (Hall et al., 1999). Although dietary pectin and oligofructose are likely to be completely degraded by ruminal bacteria and, therefore, not reach the hindgut of ruminants, this allowed us to deliver a precise amount of carbohydrate to the hindgut of ruminally cannulated animals. The 1 kg/d dose was intended to increase carbohydrate disappearance in the large intestine to an extent similar to the maximum increases observed by dietary manipulations in studies using ileally cannulated lactating dairy cows. Pectin or oligofructose recovery in feces was minimal, indicating that the entire 1 kg/d dose was fermented by gut microbes (Gressley and Armentano, 2005, 2007).
Compared with the 0 kg/d infusions, cows receiving 1 kg/d of pectin or oligofructose did not show overt signs of hindgut acidosis, as was indicated by lack of treatment effects on fecal pH or total VFA concentration. However, abomasal NDSF infusion reduced total-tract apparent digestibility of OM and starch (Gressley and Armentano, 2005, 2007). One cause for the decrease in nutrient digestibility observed with the NDSF infusions could be their physical presence in the small intestine. Random interactions of NDSF with digestive enzymes and epithelial surfaces may have decreased contact between undigested feed and digestive enzymes or between absorbable nutrients and epithelial surfaces. However, small intestinal digestion was not measured in those studies, and the decrease in OM and starch digestibility could have occurred due to NDSF effects in the abomasum or small intestine. Another potential explanation is that abomasally infused pectin or oligofructose could have increased the osmolality of digesta and increased passage rate (Roberfroid and Delzenne, 1998). Such an increase in passage rate could also reduce nutrient digestibility with the NDSF infusions. Regardless of the location of these effects, increased passage of undigested feed from the rumen during SARA may similarly hinder abomasal or intestinal digestion.

In addition to NDSF infusion effects on OM and starch digestibility, we also observed that abomasal NDSF reduced total-tract apparent digestibility of N, milk fat percentage, and milk yield. Abomasal infusion of 1 kg/d of pectin into lactating dairy cows fed isonitrogenous diets decreased apparent total-tract N digestibility from 56.7 to 48.4% and from 66.0 to 62.5% in 2 experiments (Gressley and Armentano, 2005). Similarly, infusion of 1 kg/d of oligofructose decreased apparent total-tract N digestibility from 68.8 to 64.0% (Gressley and Armentano, 2007). We had anticipated this effect because there is a net conversion of blood urea N into fecal microbial protein due to the increase in microbial biomass when carbohydrates are fermented in the hindgut (Hoover, 1978). For example, infusions of fermentable carbohydrates into the hindgut of sheep consistently increased fecal N due to increased excretion of bacteria generated in the hindgut (Örskov et al., 1970; Thornton et al., 1970; Surra et al., 1997). Studies with lactating cows have similarly shown that dietary treatments that decrease ruminal starch digestibility also reduce total-tract apparent N digestibility, presumably due to increased production of microbial N in the hindgut (Plascencia and Zinn, 1996; Knowlton et al., 1998). However, based on fecal purine excretion in our studies, we calculated that only 11 to 77% of the increase in fecal N was due to an increase in fecal microbial N generated by hindgut fermentation of the NDSF substrates, with the remainder apparently due to reduced true protein digestibility (Gressley and Armentano, 2005, 2007).

To assess whether a similar relationship between hindgut digestion and apparent N digestibility exists in published research, we evaluated treatment means from 13 studies utilizing lactating dairy cows with ileal cannulas. Treatment means for OM disappearance between the ileum and the feces (i.e., percentage of total-tract OM disappearance) were plotted against apparent total-tract N digestibility (i.e., percentage of N intake) and used to generate a regression line for each study (Figure 2). Treatment means were also evaluated by mixed model meta-analysis correcting for the random effect of study (St-Pierre, 2001). The meta-analysis indicated that there was no relationship between OM disappearance between the ileum and feces and apparent total-tract N digestibility across studies. The estimates for the intercept and slope were 24.1 (SE = 12.6, \( P = 0.08 \)) and \(-0.26 (SE = 0.18, P = 0.17)\), respectively. We had expected a negative relationship based on the abomasal infusion studies, but the relationship was not significant. We concluded that treatment differences in apparent N digestibility cannot be used to assess relative treatment differences in hindgut OM disappearance.

The decrease in milk fat percentage observed with NDSF infusion was due to decreased long-chain fatty acid concentration in milk, indicating decreased dietary fat digestibility (Gressley, 2005; Gressley and Armentano, 2007). The relationship between OM disappearance between the ileum and the feces (percentage of total-tract OM disappearance) and milk fat yield (kg/d) in published lactating cow studies is presented in Figure 3. We were again expecting a negative relationship based on the decreased milk fat yields we observed with the abomasal infusion studies. However, no relationship existed as determined by mixed model meta-analysis (St-Pierre, 2001), and the estimates for intercept and slope were 1.57 (SE = 7.37, \( P = 0.84 \)) and 5.11 (SE = 7.95, \( P = 0.54 \)), respectively. Although decreased milk fat percentage with SARA is most clearly associated with increased CLA absorption and decreased production of milk short-chain fatty acids (Bauman and Griinari, 2003), reduced dietary fat digestibility would compound this problem. In summary, results of these abomasal NDSF infusion studies suggest that the dilution of small intestinal digesta contents and the increased hindgut fermentation that accompany SARA may contribute to symptoms of SARA, including decreased diet digestibility and reduced milk fat percentage.

Recent studies have shown that SARA increases blood concentrations of acute phase proteins including haptoglobin (Hp) and serum amyloid A (SAA; Plaizier et al., 2008). Acute phase proteins are mediators of a systemic inflammatory response, and their increase in association with SARA is believed to be due to bacteria, toxins, or amines from digesta entering through a breach in the gut epithelium (Plaizier et al., 2008). We have conducted 2 studies to evaluate whether increased hindgut fermentation was capable of increasing acute phase protein concentrations in the blood. When 4 nonlactating, nonpregnant cows were infused abomasally with 4 kg/d of corn starch for 12 h/d over 3 d,
2 animals displayed overt signs of illness and hindgut acidosis (Bissell and Hall, 2010). Although the amount of starch that bypassed small intestinal digestion and reached the hindgut cannot be determined, the symptoms of hindgut acidosis included fecal pH <5 and presence of blood and mucin casts in feces. However, blood Hp and α-acid glycoprotein were unaffected, although another inflammatory marker, fibrinogen, was increased in response to the infusion (Bissell and Hall, 2010). Serum amyloid A was not measured in that trial, but SAA may be a more sensitive measure of an inflammatory response. A SARA induction study found that SAA was increased when other inflammatory markers were not (Gozho et al., 2007). When Holstein steers

Figure 2. Relationship between OM disappearance between the ileum and feces as a percentage of total-tract OM disappearance \[\left(\frac{\text{OM at ileum} - \text{OM in feces}}{\text{OM fed} - \text{OM in feces}}\right) \times 100\%\] and apparent total-tract N digestibility \[\left(\frac{\text{intake N} - \text{fecal N}}{\text{intake N}}\right) \times 100\%\]. Each data point represents a treatment mean from a study using lactating cows with ileal cannulas. Different symbols represent different studies (♦, Kung et al., 1983; ■, Santos et al., 1984; ▲, Stern et al., 1985; ×, Waltz et al., 1989; Δ, Palmquist et al., 1993; *, Pantoja et al., 1994; ●, Ali Haimoud et al., 1995; +, Mabjeesh et al., 1996; ○, Younker et al., 1998; −, Arieli et al., 2001; ◊, Callison et al., 2001; -, Prestløkken and Harstad, 2001; □, Rémond et al., 2004). Regression line is shown for each study. LI = large intestine.

Figure 3. Relationship between OM disappearance between the ileum and feces as a percentage of total-tract OM disappearance \[\left(\frac{\text{OM at ileum} - \text{OM in feces}}{\text{OM fed} - \text{OM in feces}}\right) \times 100\%\] and milk fat (kg/d). Each data point represents a treatment mean from a study using lactating cows with ileal cannulas. Different symbols represent different studies (♦, Kung et al., 1983; ▲, Stern et al., 1985; Δ, Palmquist et al., 1993; *, Pantoja et al., 1994; ○, Younker et al., 1998; −, Arieli et al., 2001; ◊, Callison et al., 2001; -, Prestløkken and Harstad, 2001; ■, Fernandez et al., 2004; □, Rémond et al., 2004). Regression line is shown for each study; regression lines for Younker et al., 1998, and Callison et al., 2001, overlapped; Callison et al., 2001, is indicated by the dotted line. LI = large intestine.
were given a pulse-dose abomasal infusion of 1 g/kg of BW (~700 g) oligofructose, animals did not display signs of systemic illness, although fecal VFA concentrations increased and fecal pH and DM decreased after the infusion (Mainardi et al., 2010). Blood concentrations of Hp, SAA, and Cu, a marker of the acute phase protein ceruloplasmin, were unaffected by the infusion (Mainardi et al., 2010). Although we did not observe increases in blood concentrations of most inflammatory markers in the cow and steer trials, the lack of an increase may have been related to the relatively short infusion periods, particularly in the steer trial. Additionally, increased hindgut fermentation in the steer trial was induced by NDSF infusion, whereas dietary starch that bypasses ruminal and small intestinal digestion is primarily responsible for hindgut acidosis on farm. Further studies using different substrates, infusion rates, and infusion durations are required to quantify the inflammatory response to increased hindgut fermentation.

SUMMARY AND CONCLUSIONS

Hindgut acidosis occurs when excessive carbohydrate fermentation in the large intestine leads to an accumulation of organic acids. These acids reduce digesta pH, cause a shift in microbial populations, and can damage gut epithelium. The precise pH decline that results in hindgut acidosis is unknown at this time. Hindgut acidosis most often occurs in conjunction with ruminal acidosis when the failure of the rumen to selectively retain fermentable carbohydrates results in increased carbohydrate flow to the hindgut. Management tools such as proper ration formulation and feed management used to prevent SARA will also reduce hindgut acidosis. A breach in the gut epithelium in response to exposure to fermentation acids produced during SARA and hindgut acidosis can allow for systemic entry of bacteria, amines, or toxins and result in inflammation. Events in the hindgut may contribute to laminitis and other health disorders associated with ruminal acidosis, and a better understanding of the relationship of the hindgut to animal health is needed.

LITERATURE CITED


Hindgut acidosis

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