Mechanisms of Volatile Fatty Acid Absorption and Metabolism and Maintenance of a Stable Rumen Environment

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Introduction

As a primary energy source for ruminants, volatile fatty acids (**VFA**) have been estimated to provide up to 75% of the total metabolizable energy (Bergman, 1990). Thus, it is not surprising that diets promoting fermentation and greater production of VFA also promote greater levels of productivity (e.g. milk production) than less fermentable diets (Kolver and de Veth, 2002; Oba and Allen, 2003a,b). However, as a weak acid, VFA will dissociate in the rumen releasing a proton thereby decreasing ruminal pH under most circumstances. Thus, when production of VFA exceeds the ability to neutralize the protons, ruminal pH decreases and ruminal acidosis can occur.

Ruminal acidosis occurs in dairy (Penner et al., 2007; Penner and Oba, 2009b), and beef cattle (Bevans et al., 2005; Weirrenga et al., 2010). However, the most common form of ruminal acidosis in dairy cattle is thought to be sub-acute ruminal acidosis (SARA) whereas, lactic acidosis or acute is thought to be the primary form in beef cattle fed high-concentrate diets (Schwaiger et al., 2013a,b). Sub-acute ruminal acidosis (pH < 5.8) is caused by a rapid rate of VFA production while, for acute acidosis (pH < 5.2), the pH depression is often associated with an increase in lactic acid (Owens et al., 1998). While thresholds are used to characterize ruminal acidosis, the actual pH value that induces damage to the ruminal epithelium, alters the microbial community structure and activity, and results in depressed feed intake likely varies among animals.

Many studies have investigated strategies to reduce the risk for ruminal acidosis, but it should be recognized that low pH does not always result in reduced performance. In a meta-analysis, Kolver and de Veth (2002) reported strong negative relationships between ruminal pH and microbial N flow to the small intestine and milk production. Oba and Allen (2003a,b) reported that cows fed high starch (32% DM; corn based diets) had a mean ruminal pH that was 0.16 units below cows fed the low starch diets, but also had greater milk production (38.6 vs. 33.9 kg/d; respectively). It is not surprising that these results occur when considering that greater VFA production, and hence greater energy availability, corresponds with low ruminal pH (Allen, 1997). Thus, understanding how cattle can regulate ruminal pH is perhaps more desirable that avoiding low ruminal pH.

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Regulation of Ruminal pH

Regulation of ruminal pH is complex and involves aspects affecting VFA production and removal of acid from the rumen. While the author acknowledges that many factors can influence ruminal pH based on VFA production (e.g. rate of fermentation, meal size and frequency, and fermentation pathway), this paper will focus on strategies that remove acid from the rumen. Most previous studies have investigated dietary strategies to promote chewing activity (Allen, 1997). Chewing increases the saliva production rate and could greatly increase the supply of bicarbonate to the rumen. In fact, it is estimated that saliva contains 126 mEq/L of bicarbonate and may contribute to approximately 30% of the total ruminal buffering capacity (Allen, 1997). However, for cattle fed low physically effective fibre (peNDF) diets such as for finishing cattle, it could be expected that the salivary contribution is much lower. The other major contributor to the regulation of ruminal pH is VFA absorption (Allen, 1997; Penner et al., 2009a; Aschenbach et al., 2011), which has been estimated to account for up to 53% of the ruminal buffering capacity (Gäbel et al., 1991; Allen, 1997). This paper will describe the current understanding of the mechanisms involved in VFA absorption and how absorption helps to stabilize ruminal pH.

Mechanisms of VFA Absorption and Implications on Ruminal pH

Mechanisms of VFA Absorption

While many textbooks supported the concept that VFA absorption occurs via passive diffusion, pioneering work (Danielli et al., 1945; Masson and Phillipson, 1951; Ash and Dobson, 1963) clearly showed that VFA were absorbed across the ruminal wall and that absorption was associated with the appearance of bicarbonate and carbon dioxide in the buffer solution. Unfortunately those authors were not able to confirm the mechanisms for VFA absorption, they did provide the first evidence that VFA absorption was linked to ruminal pH. Subsequently, Dijkstra et al. (1993) reported that the rate of VFA absorption increased with decreasing pH and that the increase in absorption was linear to the reduction in pH. Given the lack of saturation in the absorption rate with increasing concentration of VFA and an increase for the absorption of VFA with lower pH, absorption had to a large extent been thought to occur via passive diffusion (Dijkstra et al., 2003; López et al., 2003; Graham et al., 2007). It is important to recognize that as pH declines, the proportion of VFA that would be in the undissociated state increases and that only undissociated VFA are permeable across the lipid bilayer of cells (Walter and Gutknecht, 1986; Gäbel et al., 2002). Thus, a reduction in pH would increase the proportion of undissociated VFA that could then freely diffuse across the rumen epithelium.

While evidence seemed to support the theory of passive diffusion, there are numerous theoretical constraints. Firstly, the proportion of VFA in the undissociated state is low under normal pH conditions in the rumen. Volatile fatty acids have a pKa of approximately 4.8. Even with pH values of 5.8, more than 90% of the VFA would be in the dissociated state and thus only a small fraction would be lipophilic and it could be

expected that the rate of VFA absorption would proceed slowly. Although the relative proportion of undissociated VFA would be low, it was suggested that there was an acidic pH microclimate on the luminal side of the ruminal epithelia (Graham and Simmons, 2005). This microclimate could then favor VFA to be in the undissociated state adjacent to the epithelium thereby promoting absorption. However, the pH on the surface of the epithelia has been reported to be basic with values ranging between 7.47 and 7.68 depending on the incubation conditions (Leonhard-Marek et al., 2006). Limitations to the model of exclusive passive diffusion also extend to differences for the lipophilicity of individual VFA. Lipophilicity from greatest to least is butyric acid > propionic acid > acetic acid (Walter and Gutknecht, 1986), and as such it could be expected that the rates of absorption would be greatest for butyrate > propionate > acetate when corrected for concentration in the rumen. However, similar fractional absorption rates have been reported among VFA in vitro (Aschenbach et al., 2009) and when differences are found (Dijkstra et al., 1993; López et al., 2003), they are not consistent with the increase that would be predicted based on lipophilicity (e.g. butyric acid is 14 times greater than acetic acid; Walter and Gutknecht, 1986). Moreover, a recent study showed that although the concentration of VFA increased from 10 to 50 m*M*, the rates of acetate and butyrate absorption only increased by 2.1 and 2.4 times for acetate and butyrate, respectively (Schurmann, 2013).

Numerous studies have been conducted to determine the mechanisms for VFA absorption across the rumen epithelium. A model showing the current understanding of the mechanisms involved in VFA absorption and how the absorption of VFA contributes to the stabilization of ruminal pH is depicted in Figure 1. The predominant mechanisms include; 1) VFA^-/HCO_3^- anion exchange, 2) passive diffusion, 3) nitrate-sensitive VFA absorption, 4) proton-coupled VFA^- transport, and 5) electrogenic VFA transport. While these are the major absorption mechanisms, other processes such as Na/H exchange, and bicarbonate import into the cell are required to enable the maintenance of intracellular pH and to promote VFA absorption.

Pathway of VFA Absorption and the Removal of Protons from the Rumen

Few studies have aimed to determine the relative proportion of the various VFA transport processes. However, based on the available data it appears that for acetate the proportion accounted for by bicarbonate-dependent transport, nitrate-sensitive transport, and passive diffusion are 42 to 57%, 0 to 14%, and 29 to 59% respectively (Penner et al., 2009a; Schurmann, 2013). For butyrate, the proportion accounted for by bicarbonate-dependent transport, nitrate-sensitive transport, and passive diffusion are 24 to 46, 0 to 4, and 25 to 76%, respectively (Penner et al., 2009a; Schurmann, 2013).

In the rumen, the vast majority of the VFA will be in the dissociated state (**VFA^-**). Absorption of VFA^- occurs in exchange for HCO_3^- in an electro-neutral process that is mediated by a number of potential anion exchangers (Bilk et al., 2005; Aschenbach et al., 2009; Penner et al., 2009b). This mechanism provides a source of bicarbonate to the ruminal environment where it can neutralize a proton via the carbonic anhydrase reaction producing carbon dioxide and water. Driving forces for bicarbonate-dependent

transport include the concentration of ruminal VFA and ruminal pH. In fact, the bicarbonate-dependent VFA absorption increases with increasing luminal VFA concentration and with decreasing ruminal pH (Aschenbach et al., 2009). The bicarbonate facilitating this transport does not seem to occur in the cytosol, but rather is transported from arterial circulation into the cell (Sehested et al., 1999; Aschenbach et al., 2009). There are several bicarbonate transporters including anion exchangers on the basolateral (blood-facing) side that may also help to export VFA^- out of the cell and into arterial blood. Thus, it appears that this transport process is crucial in terms of helping to regulate ruminal pH (Penner et al., 2009a) and exporting VFA to be metabolized by other tissues.

Passive diffusion of VFA seems to occur, but it should be acknowledged that the contribution of passive diffusion towards VFA absorption declines as more transport processes are defined. When VFA are absorbed via passive diffusion, 1 proton is removed from the ruminal contents; however, upon appearance in the cytosol, VFA will rapidly dissociate. The proton released then needs to be expelled from the cell in order to maintain intracellular pH and tissue integrity. Transporters involved in the regulation of intracellular pH include the sodium/hydrogen exchangers **(NHE)** that export protons back to the lumen or into extra-cellular spaces. In addition to NHE, the monocarboxylate transporter **(MCT)** has been shown to be localized on the basolateral membrane (blood facing; Graham and Simmons, 2007) and can facilitate the removal of a proton along with metabolic end-products of VFA metabolism such as ketone bodies and lactate (Müller et al., 2002; Kirat et al., 2006). Thus, the direction of proton export has major implications for whether passive diffusion contributes to the stabilization of ruminal pH. For example, if the proton is exported back into the rumen contents as a strategy to maintain intracellular pH, there would be no net proton removal from the rumen and therefore ruminal pH would not be affected. Interestingly, the expression and activity of NHE in ruminal epithelia increase when highly fermentable diets are fed (Etschmann et al., 2009; Yang et al., 2009; Schurmann, 2013). However, due to the complexity of the transport mechanisms involved and the regulation of their activity, it is very difficult to quantify or predict the proportion of protons recycled back to the lumen relative to those that account for permanent removal from the ruminal contents. That said, it is clear that under some circumstances passive diffusion does contribute to the removal of protons from the rumen (Penner et al., 2009a).

In addition, it is now known that there is a nitrate-sensitive transport pathway for VFA. This process occurs both in the presence and absence of bicarbonate (Aschenbach et al., 2009), but currently the transporters involved are not known. Recent unpublished work (K. Wood, J.R. Aschenbach, F. Stumpff, and G.B. Penner) has shown a clear inhibitory effect with increasing concentrations of nitrate for acetate but no effect for butyrate. Future studies are required to improve our understanding of this transport mechanism and its regulation.

Finally, electrogenic VFA^- transport has been documented (Stumpff et al., 2009; Georgi et al., 2013). This transport process is thought to be mediated by maxi-anion channels but the total contribution to VFA transport is not currently known.

Evidence Linking VFA Absorption to the Stabilization of Ruminal pH

Early studies (Masson and Phillipson, 1951; Dobson and Ash, 1963; Gäbel et al., 1991) had suggested that VFA absorption could be one mechanism for the stabilization of rumen pH. While not an intended outcome, Dijkstra et al. (1993) reported that when artificial buffers were placed in the evacuated and washed rumen of dairy cows, pH increased to 7.1, 8.0, 8.2, and 8.2 from initial pH values of 4.5, 5.4, 6.3, and 7.2, respectively. Several reviews (Allen, 1997; Gäbel et al., 2002; Aschenbach et al., 2011) have suggested that VFA absorption should help to stabilize ruminal pH when evaluating the mechanisms involved in VFA transport. Despite the suggestions, the hypothesis was not proven correct until recently.

The first evidence supporting the pH stabilizing effect of VFA absorption was provided by Resende Júnior et al. (2006). In that study moderate (r^2 = 0.43) positive correlations between the fractional rate of VFA clearance and ruminal pH were observed suggesting that greater rates of VFA clearance corresponded to improved ruminal pH. Resende Júnior et al. (2006) further evaluated whether the effect on pH was due to absorption of VFA across the rumen wall or the passage of VFA out of the rumen finding that both mechanisms were positively related to ruminal pH. In another study Penner et al. (2009b), reported negative associations between the expression of a number of genes involved in VFA metabolism and the severity of ruminal acidosis for dairy cows fed a diet containing 64% concentrate. While these studies (Resende Júnior et al., 2006; Penner et al., 2009b; Schlau et al., 2012) showed relationships between ruminal pH or the severity of ruminal acidosis and the absorption of VFA or indicators for intra-epithelial metabolism of VFA, they cannot prove that VFA absorption improves ruminal pH nor can they elucidate how the pathway of VFA and type of VFA affect ruminal pH.

Penner et al. (2009a) conducted a study to determine the relationship between the uptake of VFA and the severity of ruminal acidosis. In that study, ruminal acidosis was induced in 17 lambs using an oral glucose drench (5 g glucose/kg BW). Based on the ruminal pH response over 3 hours after the drench, lambs were assigned to 1 of 2 classifications; non-responders (**NR**; the 7 lambs that had the least ruminal pH reduction) or responders (**RES**; the 7 lambs that had the greatest reduction in ruminal pH following the challenge). To evaluate the relationship between ruminal pH and VFA absorption, the rumen epithelium was collected and the uptake of acetate and butyrate was measured ex vivo. Results from the NR and RES lambs were compared to a group that was not exposed to an acidotic challenge (**SHAM**). Ruminal pH differed between sheep classified as NR (67.8 min), RES (153 min) and SHAM (1.1 min) as did the uptake of acetate and butyrate. It is important to note that we assumed that the acidotic challenge imposed did not compromise the ruminal epithelium as acetate and butyrate uptake did not differ between the RES and SHAM treatments. Interestingly, we found that epithelia from NR sheep had a greater rate of total acetate and butyrate uptake than RES indicating that the improved ruminal pH response could be attributed to greater capability for VFA uptake. In addition, retrospective correlation analysis showed that acetate and butyrate uptake was also positively related to the mean pH prior to the

acidotic challenge. This is the only study (Penner et al., 2009a) that has provided comprehensive data demonstrating that the rate of acetate and butyrate uptake has a substantial effect on ruminal pH homeostasis.

As mentioned above, the pathway of VFA absorption may play a role in the stabilization of ruminal pH. In addition to total uptake, Penner et al. (2009a) also reported that the main mechanisms facilitating acetate and butyrate uptake were different between NR and RES. For acetate, the bicarbonate-dependent and bicarbonate-independent nitrate-sensitive transport was greater for NR than RES. As mentioned above, with the bicarbonate-dependent transport, bicarbonate secretion and acetate absorption are coupled. Interestingly, for butyrate, bicarbonate-independent (passive diffusion) uptake was higher for NR than RES. Collectively these data indicate that the pathway of VFA absorption may differ based upon the type of VFA and thus the relative contribution towards the stabilization of ruminal pH may also differ. For example, acetate is not as lipophilic as butyrate and thus protein-mediated pathways contribute substantially towards its uptake. This is important as the bicarbonate-dependent pathway would also provide bicarbonate to buffer the rumen contents (Aschenbach et al., 2009). In contrast, butyrate has a greater potential for diffusional uptake (Walter and Gutknecht, 1986). Thus, factors promoting a concentration gradient between the rumen, cytosol, and blood should promote absorption (Gäbel et al., 2002). The suggestion that intracellular metabolism enhances butyrate absorption is in alignment with Gäbel et al. (2001) and previously reported negative correlations between the expression of genes involved in butyrate metabolism and the severity of ruminal acidosis (Penner et al., 2009b). Furthermore, we found that NR sheep had greater serum β-hydroxybutyric acid **(**BHBA (**BHBA**; a metabolite of butyrate metabolism) that RES sheep after the 180 min acidotic challenge (Penner et al., 2009a). The increase in serum BHBA may also indicate that for butyrate, metabolism to ketone bodies and export from the cell via MCT may help to regulate ruminal pH.

A clear limitation with our understanding of VFA transport is that most studies have only evaluated acetate and butyrate transport thereby omitting propionate and longer chain VFA. Based on lipophilicity (Walter and Gutknecht, 1986) and the extent of metabolism by the rumen epithelium, it is expected that propionate transport would be intermediate to acetate and butyrate and thus have a high reliance on bicarbonate-dependent transport (Aschenbach et al., 2009). Based on the current data available it is evident that VFA absorption helps to stabilize ruminal pH and that the relative effect of individual mechanisms (passive diffusion, bicarbonate-dependent transport) for absorption differs based on the VFA (acetate, propionate, and butyrate) absorbed.

Nutritional Modulation of VFA Transport

Given the importance of VFA transport towards meeting the energy requirement and stabilization of ruminal pH, several studies have investigated whether dietary or feeding management can modulate the response. Interestingly, past studies have clearly demonstrated that feeding management can both positively and negatively influence VFA absorption.

Feed Restriction and Feed Deprivation Decrease VFA Absorption

The vast majority of current research has focused on rumen epithelial adaptation from an anabolic perspective, however, in times of scarcity or in response to a nutritional insult, the adaptive response certainly includes regression. In fact, the long-term changes induced by a low plane of nutrition have been shown to decrease gut mass and reduce O_2 consumption by visceral tissue, and reduce VFA absorption (Doreau et al., 1997). Understanding how the ruminal epithelium responds to reductions in VFA production due to a transient exposure to feed restriction and, more importantly, the timeline required for the epithelium to return to the pre-restriction function is needed to develop feeding strategies and mitigate disorders associated with digestive upset.

Albeit unintentional and generally short in duration, beef and dairy cattle are exposed to periods of feed restriction or complete feed deprivation. Examples include during weaning, transportation, prior to and immediately after parturition, immediately following digestive upset, while experiencing heat stress, and in association with metabolic disorders and infection. Gäbel et al. (1993) demonstrated that 48-h of complete fed reduced VFA, Na^+, Ca^{2+}, and Mg^{2+} absorption by approximately 40 to 60%. It is important to note that these changes were likely due to a reduction in the functional capacity and blood flow rather than changes induced by epithelial surface area. More recently, the effect of the severity of short-term feed restriction, rather than complete feed deprivation, has been investigated (Zhang et al., 2013a). In this study, 18 heifers were fed ad libitum and then allocated feed equating to 75, 50, or 25% of their ad libitum DMI for a period of 5 d. A 5-d feed restriction period, regardless of the severity, tended (P = 0.09) to decrease total VFA absorption and decreased acetate absorption. Additionally, heifers restricted to 50 and 25% of ad libitum intake tended (P = 0.07) to have lower rates for total VFA and acetate absorption compared to those restricted to 75% of ad libitum intake. It does not appear that shifting the dietary forage-to-concentrate ratio will mitigate this effect despite expected changes in fermentability and ruminal retention time (Albornoz et al., 2013a). For example, when cattle were restricted to 25% of their ad libitum intake for 5 d, the total VFA absorption rate decreased by 120 mmol/h relative to baseline measurements and did not differ between heifers fed a diet consisting of 92% forage vs. those fed 60% forage (Albornoz et al., 2013a). Thus, it appears that reductions in ruminal epithelial function occur rapidly in response to lower energy intake.

A rapid reduction in ruminal epithelial function may be a compensatory mechanism to reduce energy expenditure by ruminal tissue (Zhang et al., 2013a) during periods of low energy intake. However, given the transient nature of low feed intake under conventional feeding systems, a rapid increase in epithelial function corresponding to increased energy intake would be desirable. Zhang et al. (2013b) provided heifers ad libitum access to feed, without changes in the diet composition, after a 5-d period of feed restriction. That study reported two important findings: 1) return to ad libitum feeding without dietary change induced ruminal acidosis, and 2) that time to recover absorptive function increased with increasing severity of feed restriction. In fact, heifers restricted to 25% of their ad libitum intake required 3 week for VFA absorption

rates to recover, whereas those restricted to 75% of their ad libitum intake recovered within 1 wk. The delayed recovery response suggests that at least a portion of the response is mediated by the epithelia and not solely due to changes in blood flow. Interestingly, the recovery response appears to be hastened when cattle are fed greater proportions of concentrate prior to dietary restriction and greater proportions of forage after feed restriction (Albornoz et al., 2013b). Future work is needed to develop strategies that can be used to mitigate a reduction in epithelial function in response to transient nutritional challenges and to accelerate the rate of recovery in response to feed restriction or feed deprivation.

Ruminal Acidosis Compromises VFA Absorption

Providing adequate time for dietary adaptation has been recommended as a strategy to reduce the risk for ruminal acidosis. It is evident that repeated exposure to sub-acute ruminal acidosis or a single exposure to acute ruminal acidosis may also negatively affect VFA absorption. Dohme et al. (2008) reported that the response to repeated ruminal acidosis inductions increased in severity with each consecutive challenge despite the cows consuming less grain during consecutive challenges. While there may be a number of reasons behind this response, a decrease in VFA absorption is highly plausible because previous studies have shown that at similar pH values (< 5.4) epithelial damage was induced (Steele et al., 2009) and ion transport was impaired (Gaebel et al., 1987, Gaebel et al., 1988; Gaebel et al., 1989). That said, it is not clear whether adaptation reduces the risk for ruminal acidosis. In a recent study, we compared whether cattle fed a high-grain diet (81% barley grain, 10% vitamin and mineral supplement, 9% barley silage) for 34 d were more resistant to ruminal acidosis than cattle fed the same diet but for only 8 d (Schwaiger et al., 2013a,b). Ruminal acidosis was induced by restricting feed intake on the d before the challenge and the challenge itself included an intraruminal infusion of ground barley grain. There were no differences observed for the risk or severity of ruminal acidosis between short-adapted and long-adapted cattle. However, we did observe that ruminal pH recovered more rapidly in long-adapted cattle than short-adapted cattle. Interestingly, long-adapted cattle also had greater lactate absorption than short-adapted cattle immediately following the challenge.

While the total VFA absorption rate was not different between the short- and long-adapted cattle, it was very clear that induction of ruminal acidosis decreased VFA absorption (Schwaiger et al., 2013a,b) when measured 2 d following induction of ruminal acidosis but not when measured 9 d after the induction of ruminal acidosis (Figure 2). Moreover, there appears to be a compensatory shift in ruminal buffering strategies such that absorption is reduced following a bout of ruminal acidosis while at the same time, saliva production increases (Figure 2). Thus, it appears that ruminal acidosis impairs VFA absorption but the recovery following a bout of ruminal acidosis may be rapid and that cattle may increase salivary buffer supply to compensate for the reduction in VFA absorption. The negative effect of severely low ruminal pH on VFA absorption is supported by previous work in vivo (Krehbiel et al., 1995) and in vitro (Wilson et al., 2012).

Understanding Adaptation of the Rumen Epithelium and VFA Transport in Response to an Increase in Diet Fermentability

In conventional production systems cattle are exposed to abrupt dietary change. Examples include Holstein calves at weaning, beef cattle upon arrival at a feedlot, and immediately following calving for transition dairy cattle. Interestingly, all of the above-mentioned situations have also been suggested as periods with high risk for ruminal acidosis. Previous literature had suggested that 4 to 8 weeks were required for maximal increases in the absorptive surface area of the ruminal epithelium (Dirksen et al., 1985; Bannink et al., 2008); however, more recent evidence has suggested that changes in the functional activity precede increases in surface area (Etschmann et al., 2006).

Schurmann (2013) used 25 Holstein calves to determine the rate of epithelial adaptation when exposed to an abrupt dietary change focusing on the absorptive surface area of the ruminal epithelium and the rate and pathway of VFA absorption. In that study, calves were fed a diet containing 92% grass hay and 8% mineral and vitamin pellet and then abruptly changed to a diet containing 50% grass hay, 42% ground barley grain, and 8% mineral and vitamin pellet. Calves were fed the latter diet for 0, 3, 7, 14, and 21 d before they were killed to measure VFA transport rate and the pathway of transport. Ruminal pH responded quadratically with an initial decrease until d 7 and then increasing to d 21. This finding supports previous work by Steele et al. (2011) when dairy cattle were abruptly exposed to a diet change. Moreover, effective surface area of the ruminal papillae was not affected by treatment indicating that changes in absorption rates for acetate and butyrate could be attributed to functional changes in the epithelial cells rather than increased size or abundance of cells. For acetate, the rate of transport increased by 18% within 7 d of feeding the 50% forage diet whereas, butyrate increased (27%) linearly from d 0 to d 21. While it was hypothesized that the increase would primarily be due protein mediated transport processes such as anion exchange, the only pathway affected was passive diffusion. This indicates that changes in epithelial cell permeability may be one strategy to facilitate a rapid increase in VFA absorption; however, this approach does not necessarily correspond to an improvement in ruminal pH.

Conclusions

Short-chain fatty acid absorption clearly helps to stabilize ruminal pH by either removing protons with passive diffusion or by the secretion of bicarbonate with anion exchange mechanisms. Interestingly, the relative contribution of individual pathways of VFA absorption differ based on the type of VFA absorbed and moreover, the contribution of salivary bicarbonate and epithelial buffering towards stabilization of ruminal pH appear to be affected by ruminal pH itself. A number of factors such as feed deprivation and feed restriction and ruminal acidosis negatively affect VFA absorption and thereby increase the risk for ruminal acidosis. Future research is needed to determine how nutritional management can be used to enhance the absorptive function of the ruminal epithelia in effort to mitigate ruminal acidosis and improve nutrient delivery.

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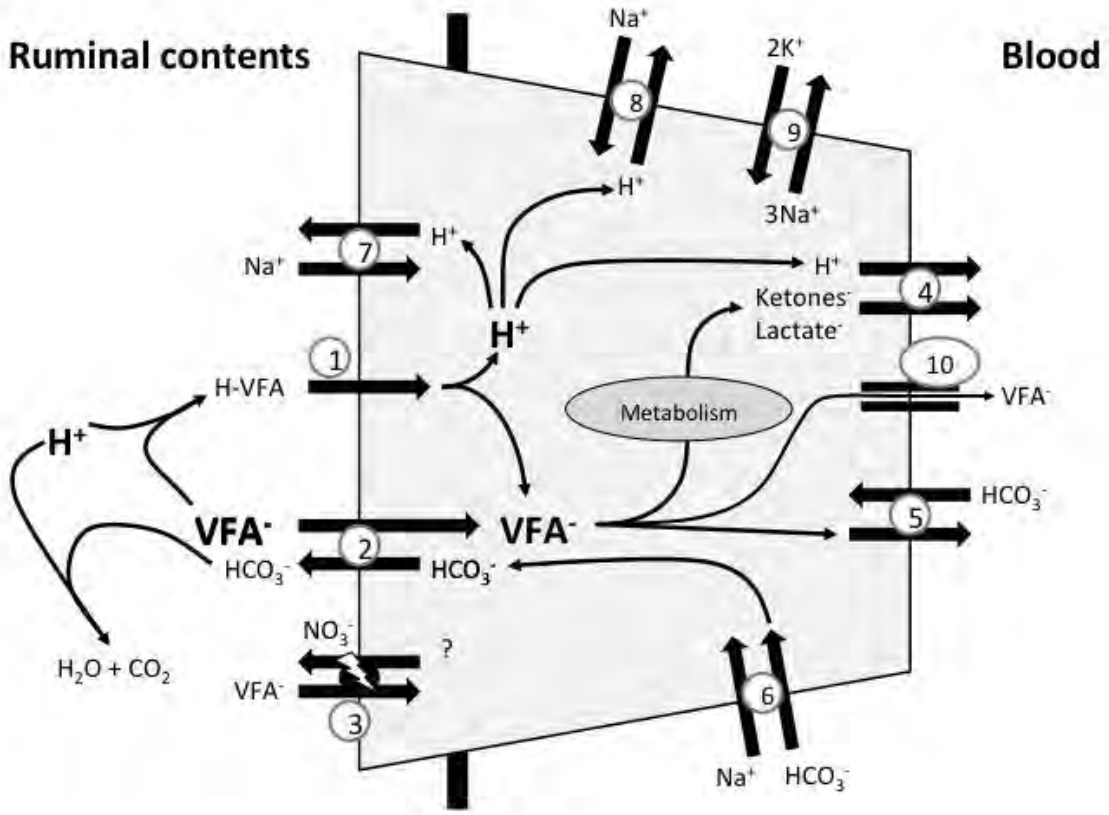

Figure 1. Partial model depicting the current understanding for SCFA absorption in relation to the stabilization of ruminal pH. 1) Diffusional absorption of SCFA facilitates the removal of a proton associated with the SCFA. This proton will rapidly dissociate in the cytosol where it can be exported by sodium/hydrogen exchanges (7, 8) or coupled with metabolites of SCFA (e.g. ketone bodies and lactate) via the monocarboxylate transporter (4). Dissociated SCFA can be absorbed in an anion exchange mechanism thereby providing a source of bicarbonate to the ruminal contents (2). This bicarbonate can then neutralize a proton through the carbonic anhydrase reaction thereby stabilizing ruminal pH. The bicarbonate supply to the epithelia is derived from blood (5, 6). The VFA can also be absorbed via a nitrate sensitive pathway (3) and can be exported into blood via a voltage-gated channel (10). Note, the model does not show the structural complexity of the ruminal epithelia including the number of strata and cells within strata. Adapted from Aschenbach et al. (2011).

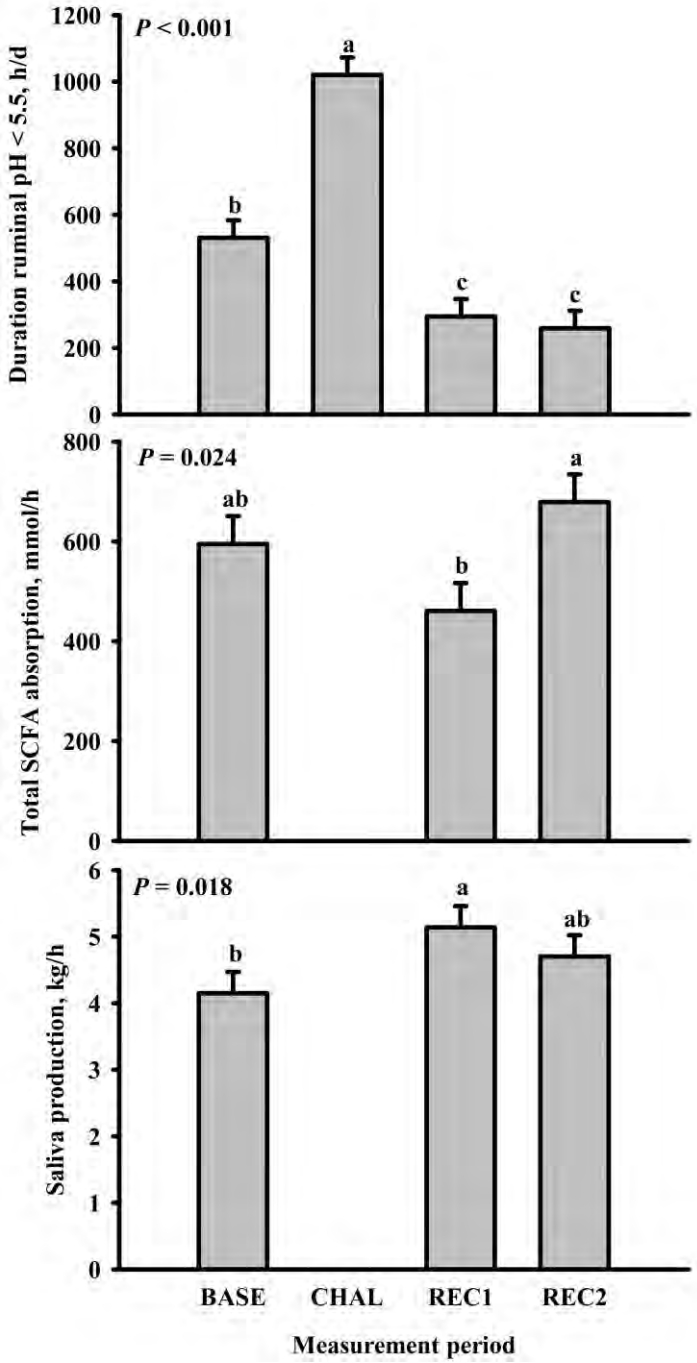

Figure 2. Changes in ruminal pH (panel A) in response to inducing ruminal acidosis and the corresponding changes in VFA absorption across the temporarily isolated reticulo-rumen (panel B), and saliva production (panel C) in beef heifers fed a high-concentrate diet.

SESSION NOTES