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Utilization and Addition Sugars to Ruminants Rations

Jalal Bayati Zadeh[*1], Zahra Moradi Kor [1]

[1] Young Researchers and Elites Club, Sirjan Branch, Islamic Azad University, Sirjan, Iran

ABSTRACT

Responses to sugars in dry or liquid formvary from study to study. When fed in proper amounts, sugars should not depress ruminalpH, and there is some evidence that they actuallyhelp toprevent a drop in pH after consuming largemeals of concentrate by maintaining a highernumberoflactate-fermenting bacteria. Adding sugars doesprioritize the need for rumen degraded protein (RDP).we all know, sugars are rapidly and extensively fermented. Also, it pretty well established that there is an optimum feeding rate between 2.5 and 5% supplemental sugar. Carbohydrates are the main components in the dairy ration, comprising roughly 60 – 80% of total dry matter (DM) and could supply to 70% net energy lactation (NEL) for high yielding dairy cows. The relatively high rate of absorption of ammonia by ruminants (Huntington, 1990) suggests that energy availability, or lack of synchrony between energy and nitrogen supplies, limits the use of available nitrogen by ruminal microorganisms.

Key words: Sugers, Starch, Utilization, Ruminants

INTRODUCTION

The ruminant digestive system provides the powerful advantage of pregastric fermentation that enables the use of structural carbohydrates and the production of microbial protein to meet the needs of the host. This complexity of ruminant digestion also offers a challenge towards optimizing nutrient supply for the host. Despite the advantages for use of structural carbohydrates, the system is not optimally designed for use of non-structural carbohydrates. The pregastric fermentation results in fermentation losses of 13-18% of gross energy (Harmon and McLeod, 2001) and is at risk of carbohydrate overload if excessive amounts are consumed (Dunlop, 1972). As we all know, sugars are rapidly and extensively fermented. Also, it pretty well established that there is an optimum feeding rate between 2.5 and 5% supplemental sugar (Firkins et al., 2008b), but it is not clear in what diets sugars are more effective and in which form to use them. There has been much interest in feeding sugars to dairy cattle in the last few years. One difficulty has been that there is little information on how sugars fit with other ration components (protein fractions, fiber, starch, pectins, etc.), precisely what nutrients they provide to cattle, and what total levels of sugars are in rations. Precise information is not available on sugar feeding levels or how they can be used to

Corresponding Author E-mail: Bayati261@yahoo.com

enhance production. Energetically, small intestinal digestion offers efficiency advantages over ruminal fermentation of non-structural carbohydrates thus digestion in the small intestine must be optimized. We have calculated that small intestinal starch digestibility must be at least 75% or the energetic inefficiencies of large intestinal digestion result in a decreased efficiency of postruminal starch digestion. To be able to formulate diets for optimum efficiency of digestion, we must be able to optimize digestion in the different regions of the gastrointestinal tract. We must be able to take advantage of the increased efficiency of having the starch digested and absorbed as glucose in the small intestine, thus avoiding energetic losses of ruminal fermentation. To optimize diet formulation we must understand the limitations of the animal to digest and absorb both structural and non-structural carbohydrates thereby preventing the inefficiency of large intestinal fermentation. Although a low ratio of effective fiber:rumendegraded carbohydrate has long been associated with milk fat depression, most studies with sugars are neutral or actually support a higher production of milk fat (see below). In order to understand when and how sugars could increase milk fat yield, we must address some critical mechanisms. One obviously critical component is enhanced DMI, which obviously increases NEL intake needed for production of energy-corrected milk (including milk fat), but DMI also is the most critical driving variable positively related to microbial protein synthesis (Oldick et al., 1999) in a variety of dietary conditions and to milk protein yield when cows are fed supplemental fat (Wu and Huber, 1994). Milk fat yield is limited by fatty acid synthesis in the mammary gland, so we must evaluate whether or not sugars will foster ruminal production of *trans* fatty acids that can pass to the intestine and depress milk fat secretion (Jenkins et al., 2008). Finally, these factors might interact with the source and particle length of forage. My objectives are to integrate the ramifications of these factors when considering sources of sugars in dairy rations.

Sugars: Definitions

“Sugars” will be defined for the purposes of this paper as monosaccharides (simple sugars), disaccharides, and oligosaccharides. Analytically, carbohydrates are separated from polysaccharides (long chains of monosaccharides) by their solubility in 80% ethanol. Sugars are nonfiber carbohydrates (NFC), as well as nonstructural carbohydrates (NSC), because they are not included in NDF and are found in the cell contents. Glucose and fructose are the simple sugars most commonly found in plants (Figure 1). The most abundant disaccharide in plants is sucrose, which is a molecule of glucose bonded to fructose. Lactose (glucose + galactose) is found in milk. Maltose is a disaccharide with the same glucose-to-glucose alpha-linkage as starch. Oligosaccharides are chains of monosaccharides that are two to approximately 20 units long. They include stachyose and raffinose found in soybeans (Smith and Circle, 1978), as well as short chain fructans found in cool-season grasses. Except for some of the cool-season grasses, plants do not generally have a large oligosaccharide content. The sugar content of feedstuffs can vary greatly . Mature grains such as corn or oats may contain very little sugar because most of it has been converted to starch. Forages, such as pasture or hay, may have relatively greater amounts of sugars (2 to 12% of dry matter for alfalfa hay; R. Ward, Cumberland Valley Analytical Services, personal communication). The levels in hay are likely to vary with harvest management and how much the plant respires away during the wilting process. By-product feeds, such as molasses, bakery waste, citrus pulp, and almond hulls, tend to have high contents of sugars. However, the variation in processing methods and source material can lead to great variation in sugar content. For example, citrus pulp samples analyzed in our laboratory varied from 12 to 40% sugars on a dry matter (DM) basis. With molasses, the information supplied on the total sugars as invert is a nutritionist’s best guide for the sugar value to place on the feed. Calculation of NFC in molasses (100 – crude protein – NDF – crude fat – ash) as a proxy for sugar content will overestimate both. Molasses may contain 10 to 15% of DM as compounds such as Maillard

products and organic acids that are not analyzed for by usual feed analysis methods and so fall by default into NFC (Binkley and Wolfram, 1953).

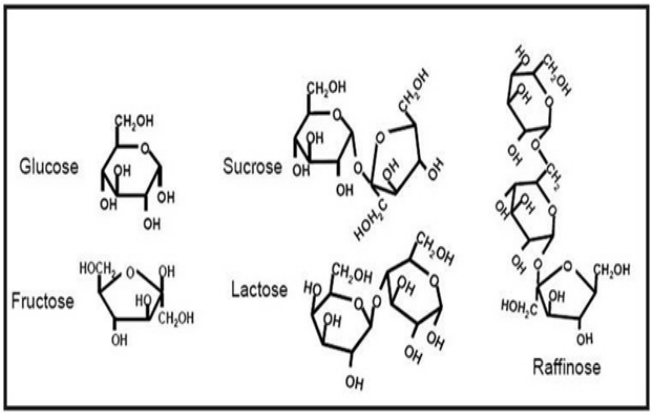

Figure 1. Chemical structures of sugars.

To more accurately describe the carbohydrate content of molasses in feed evaluation programs, add the value of (NFC – total sugars as invert) to the measured ash content of molasses; this will roughly account for the non-carbohydrate materials included in NFC and will prevent overestimation of the available carbohydrate, but it will underestimate the organic acid content.

Carbohydrate degradation in the rumen

Carbohydrates are the main components in the dairy ration, comprising roughly 60 – 80% of total dry matter (DM) and could supply to 70% net energy lactation (NEL) for high yielding dairy cows. Therefore understanding carbohydrates features and applying their characteristics for the formulation of dairy rations are important for improving milk production and animal health. As the main reservoir of photosynthetic energy in plants, plant carbohydrates composed of 50 – 80% of the DM of forages and cereals (Van Soest, 1994). The carbohydrates in the feed can be divided into two fractions, namely fibre and non-fibre fractions. Fibre fraction, commonly referred to structural carbohydrates (SC) include cellulose, and hemicelluloses. Non structural carbohydrates (NSC) include starch, pectin, and sugars (Van Soest, 1994). In ruminants, nearly all carbohydrate digestion (> 90%) occurs in the rumen (Armstrong and Smithhard 1979), although in some cases, such as at a high rate of passage, a significant portion of NSC digestion can occur in the small intestine (Nocek and Tamminga 1991). The simple sugars found in plant cells are glucose, fructose, and sucrose. They are rapidly degraded in the rumen to yield short chain fatty acids (SCFA), which are absorbed into the blood through the rumen wall. Polysaccharides must be hydrolysed into simple sugar before being utilized. Starch as a NSC is easily degraded in the rumen while degradation of structural carbohydrates, such as celluloses and hemicelluloses, varies considerably (Baldwin and Allison 1983). Cellulose degradability of forages varies from 30 – 90% while hemicelluloses digestibility varies from 45 – 90% (Van Soest, 1994). This broad range of cellulose and hemicelluloses digestibility from the different feeds is mainly due to lignification. Therefore the rate and extent of digestion of cellulose and hemicelluloses are related to the lignin content (Van Soest, 1994).

Ruminal Digestion of Starch

Although protozoa and fungi participate in ruminal digestive processes, the bulk of the fermentation is performed by ruminal bacteria. A key initial step in bacterial digestion of feed particles is attachment; approximately three-fourths of fiber, protein, and starch digestion is accomplished by bacteria that are loosely or tightly attached to feed particles (McAllister et al., 1994). Kotarski et al. (1992) identified 15 strains of amylolytic bacteria and characterized eight amylolytic enzymes produced by those bacteria. At least some of these bacteria adhere to and colonize grain particles in the rumen and produce endo- and exo-enzymes that hydrolyze the a1-4 and a1-6 bonds of amylose and amylopectin. However, not all bacteria are equipped with a complete array of digestive enzymes; therefore, maximal digestion of starch to monosaccharides requires integration among bacterial species. Coculture of *Streptoccocus bovis*, *Butyrivibrio fibrisolvens*, *Bacteriodes ruminicola*, and *Selenomonas ruminatium* demonstrated the importance of crossfeeding among bacterial species in attaining greatest bacterial growth rates and complete digestion of starch (Cotta, 1992). Ruminal protozoa play a role in the process by ingesting and digesting starch granules (with or without bacteria attached). Rate and extent of ruminal starch digestion were greater when protozoa were eliminated from the rumen of sheep fed high-moisture corn and dry-rolled sorghum (Mendoza et al., 1993). The hyphae of fungi may play an important role in bacterial attachment by creating lesions in the surface of plant tissue (McAllister et al., 1994).

Animal Studies

There have been relatively few animal performance studies using purified sugars. Two studies in mhich sucrose was substituted for starch in lactating dairy cow rations suggest that sucrose increases milk fat yield, but other results are mixed. When sucrose was substituted for corn meal at 1.5% of ration DM, intake, milk yield, and fat-corrected milk yield did not change, but milk fat yield increased from 2.12 to 2.14 lb per day, and milk protein decreased from 3.51 to 3.28% (Nombekela and Murphy, 1995). In alfalfa silage + corn silage + high-moisture shell corn diets where sucrose was substituted for corn starch (0 to 7.5% of dietary DM, diet NFC ~ 43% of DM; Broderick et al., 2000), there were linear increases in DM intake, milk fat yield ($P < 0.05$), and a tendency for an increase in 3.5% fat-corrected milk yield ($P = 0.11$). Milk protein yield was unaffected. In terms of feed efficiency, milk yield / DM intake decreased linearly from 1.60 to 1.52 ($P < 0.02$), and the conversion of ration nitrogen to milk protein N declined linearly with increasing substitution of sucrose for starch (from ~0.312 to ~0.285; $P = 0.01$). However, the efficiency of producing 3.5% fat- and protein-corrected milk did not appear to change with diet (no statistics applied). Reports of inefficiency of CP utilization in diets containing sugars as a supplement or in molasses compared to those containing starch or corn (Bell et al., 1953) may be related to sucrose-utilizing microbes storing glycogen rather than fermenting it directly or competing with other microbial populations for nitrogen and other nutrients (Jones et al., 1998). In a study where fresh annual ryegrass was fed to lactating cows, partial replacement of ground corn with 5% sucrose supplement (brown sugar product, 83.4% sugar) had no impact on total DM intake or on milk and component yields ($P > 0.15$) (McCormick et al., 2001). Milk yield did decline ($P = 0.15$) when sucrose-supplemented diets were supplemented with expeller soybean meal, as compared to solvent soybean meal, suggesting different effects with more or less rumen undegradable protein. The difference in the results of this study as compared to that of Broderick et al. (2000) raises the question: Does the base composition of the diet affect the impact of supplemental sugars? The diets in the Broderick et al. (2000) study contained a basal level of 2.7% sugars, whereas the fresh ryegrass in the McCormick et al. (2001) study contained 3.9 to

27.7% of DM as NFC and comprised 51 to 53% of dietary DM. The NFC in ryegrass is likely to be largely comprised of organic acids, sugars, and fructans.

Sugars, Ruminal pH, and Fiber Digestibility

Because we want to efficiently degrade particulate matter before it passes from the rumen, we must optimize bacterial colonization of stems, leaves, and even starch granules. The primary cellulolytic bacteria (they also contribute to hemicellulose degradation) are less tolerant to a low pH, and if we add too much grain to the diet, fiber digestibility can be reduced. This decreased fiber digestibility is important because it could promote bulk fill limitation of voluntary feed intake. Low ruminal pH could be reducing binding by cellulolytics to particulate matter in the rumen, allowing more tolerant bacteria to initially adhere and therefore have a more favorable competition for new feed particles (Mouriño et al., 2001). After initial adhesion to newly ingested particles, bacteria must grow (divide into many more cells) to rapidly and extensively degrade that particle before passage. However, although the latter reference (and much of our thinking) focuses on ruminal pH < 6.0 as the main limitation of fiber digestibility, more current work with molecular techniques has shown that even cows with very low pH can maintain normal populations of cellulolytic bacteria (Palmonari et al., 2010). hus, because increasing concentrate usually decreases pH, Calsamiglia et al. (2008) varied forage:concentrate while maintaining different constant pH values in continuous culture. Adding acid to systematically decrease pH had a direct effect that was dose-responsive and predictive for many variables, and was much more critical than forage:concentrate. However, while confirming the important response to low pH, these pH values were maintained constantly and were distributed throughout the entire flasks by rapid stirring of pH-controlled buffer with finely ground feed particles. In contrast, pH has been long known to depend on the time after feeding, particle size, and location of those particles stratified and slowly mixed in the rumen. We need to understand why sugars should not promote acidosis to understand how they could (at least sometimes) actually benefit the bacterial community. Lactic acid is well known to be a much stronger acid than the volatile fatty acids **(VFA)**. That is, at the same molarity, lactic acid will drop the pH about one full pH unit lower compared with the same molarity of any of the VFA. Microbiologists have well characterized how the acid-tolerant microbes can ferment glucose to lactate 5 or more times faster, thus getting more energy even from a less energetically efficient pathway (Nagaraja and Titgemeyer, 2007). However, those authors discussed that, although this potential burst of lactate production can result in acute acidosis, lactic acid concentration rarely increases because its catabolism rate compensates to metabolize more lactate as more is produced until pH progressively declines below 5.5 to inhibit the lactate consumers. Moreover, supplementing sugars could actually increase pH if there is increased production of VFA that are 4 carbons or greater in chain length because these pathways would condense 2 moles of acid into one, thus artially compensating for the high ruminal digestibility of sugars. Although 2 moles of lactate can be converted to 2 moles of propionate, Piwonka and Firkins (1996) added either glucose or lactate to batch cultures. The ability to consume lactate and stimulate fiber digestibility probably depends on having adequate rumen-degraded protein **(RDP)**. Both low pH (Calsamiglia et al., 2008) and low nitrogen per se (Griswold et al., 2003) can decrease proteolysis by bacteria in continuous culture. Many bacteria and protozoa can ferment lactate, but *Megasphaera elsdenii* is most attributed to filling this niche (Nagaraja and Titgemeyer, 2007). A comprehensive metagenomics study confirmed the importance of bacterium to keep lactate concentrations low in dairy cattle fed diets promoting acidosis (Khafipour et al., 2009). Many, but not all, studies with sugars show increases in the molar proportion of butyrate or valerate (Heldt et al., 1999), and a recent molecular analysis of rumen contents from feedlot beef steers (not fed sugars) documented that those with improved feed efficiency had increased butyrate and valerate concentrations (Guan et al., 2008). These are much more important fuel sources for the rumen epithelium

than are acetate or propionate (Kristensen, 2005). For sheep fed the same acidosis challenge diets, those grouped as non responders probably had increased rates of VFA absorption in vitro from rumen epithelia samples than those grouped as responders (much lower pH), with correspondingly increased hydroxybutyrate concentrations in the blood for the non-responders (Penner et al., 2009). In addition to passive absorption removing a proton from the rumen, macetate can be absorbed as an anion with a corresponding exchange with a bicarbonate anion that would help buffer pH. In our study (Oelker et al., 2009) and several others we cited, ruminal pH was not decreased by sources of sugars in the diet. Therefore, so long as we maintain a proper environment for microbial populations, feeding less than 5% sugars rarely decreases ruminal pH and sometimes actually increases it. The ability to consume lactate and stimulate fiber digestibility probably depends on having adequate rumen-degraded protein (RDP). Both low pH (Calsamiglia et al., 2008) and low nitrogen per se (Griswold et al., 2003) can decrease proteolysis by bacteria in continuous culture. Many bacteria and protozoa can ferment lactate, but *Megasphaera elsdenii* is most attributed to filling this niche (Nagaraja and Titgemeyer, 2007). An alternative to fostering enzymatic attack within the rumen is to first expose feed to exogenous enzymes, especially those with fibrolytic activity (Beauchemin et al., 2003). However, even addition of exogenous amylase with insignificant activities against protein or fiber still stimulated NDF digestibility (Kingerman et al., 2009). The authors referenced a proposed mechanism that amylase stimulated non-cellulolytics to cross-feed with cellulolytic bacteria. These results with amylase treatment are in contrast with meta analyses showing decreased ruminal NDF digestibility with increasing starch concentration (Firkins et al., 2001; Nousiainen et al., 2009). Thus, a small amount of sugars could stimulate an optimal development/ progression of the consortium needed for efficient degradation of fiber in diets with moderate starch concentration with the caveat for an adequacy of
RDP for the consortium.

Synchronization of Ruminal Energy and Nitrogen Availability

The relatively high rate of absorption of ammonia by ruminants (Huntington, 1990) suggests that energy availability, or lack of synchrony between energy and nitrogen supplies, limits the use of available nitrogen by ruminal microorganisms. This in turn limits efficient use of dietary nitrogen for productive purposes. Synchronization of starch and nitrogen supply to the rumen reduced absorption of ammonia and increased nitrogen retention in steers (Taniguchi et al., 1995). Bayati zadeh et al. (2012) reported that the usage of discarded dates as supply energy was increased synthesis microbial protein. Synchronization of ruminal fermentability of starch and protein increased nitrogen retention of growing lambs as a percentage of nitrogen intake (Matras et al., 1991). Readily available energy from starch fermentation is conducive to increased ruminal outflow of microbial protein in cattle. For example, ruminal outflow of bacterial protein increased from 2.2 to 2.8 kg/d in dairy cows fed steam-flaked vs dry-rolled sorghum (Poore et al., 1993). Other studies with lactating cows (Herrera-Saldana and Huber, 1989; Herrera-Saldana et al., 1990a) confirm that synchronizing the ruminal fermentability of starch and protein (nitrogen) sources increases outflow of bacterial protein from the rumen. Two studies with lactating cows fed corn or barley as starch sources did not show clear response to ruminal synchronization (McCarthy et al., 1989). In one of those studies, the ability to detect responses may have been compromised by differences in intake between diets containing ground, shelled corn and steam-rolled barley (McCarthy et al., 1989). Synchronization of rumen available protein and energy is one of the conceptual methods to increase the efficiency of utilization of nutrients by the ruminants (Bayati Zadeh and Moradi kor, 2013).

Conclusions

Sugars at 2.5 to 5% offer potential benefits that should be considered when formulating dairy rations. Carbohydrates are the main components in the dairy ration, comprising roughly 60 – 80% of total dry matter (DM) and could supply to 70% net energy lactation (NEL) for high yielding dairy cows. Based on current information, recommend keeping NFC < 37% in corn silage-based diets but perhaps < 40% in alfalfa-based diets; starch should be < 25% but perhaps 25 to 28%, respectively. When NFC and especially rumen-degraded starch are kept at these moderate concentrations, sugars are more likely to stimulate DMI, NDF digestibility, and milk fat production. Adding sugars to diets with Rumensin has no indication for adding to risk of milk fat depression. Moreover, particularly when in the form of liquid feeds applied to the TMR, sugars should help reduce sorting both against forage and for the fines. Ruminal and post-ruminal effects plus feedbunk management for group-fed cows apparently can aggregate for an overall potential benefit in milk production and efficiency.

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