The Pros and Cons of Enhancing Ruminal Digestion of Starch in Dairy Cow Diets

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Introduction

There are a number of good reasons to increase the ruminal digestion of starch in dairy cow diets. Increasing ruminal digestibility of starch can increase the digestibility of starch and organic matter in the total digestive tract, which increases feed conversion efficiency, helping to reduce feed costs. Maximizing feed digestibility helps provide the energy required for high milk production. Increased ruminal digestion of starch can also increase microbial protein synthesis (MPS) in the rumen, which helps meet the amino acid requirements of high producing dairy cows. However, the potential benefits of increased ruminal starch digestibility must be weighed against the potential drawbacks. High ruminal digestion of starch can decrease fiber digestion in the rumen and increase the risk of acidosis, negating the benefits of improved starch digestion. This talk addresses the factors that affect ruminal starch digestion and how these factors can be used to improve milk production, while avoiding the negative effects on acidosis.

Ruminal vs. Intestinal Digestibility of Starch

Theoretically, fermentation in the rumen is less energetically efficient (80%) than enzymatic digestion in the small intestine (97%) (Harmon and McLeod 2001, Huntington 2006). But, digestion in the large intestine is clearly less energetically efficient (44%) than digestion in either the rumen or small intestine. Thus, from an energy efficiency perspective, it makes sense to maximize the proportion of starch digested in the small intestine. However, shifting the site of starch digestion from the rumen to the small intestine increases the need for high digestibility in the small intestine. If starch digestibility in the small intestine is low, the starch will then be fermented in the large intestine, masking any gains in efficiency achieved by sifting the site of digestion from the rumen to the intestine.

In practical feeding situations, intestinal digestibility of starch is not always high, particularly when grains are fed whole, cracked, coarsely ground or steam rolled. Ground grains usually have high intestinal digestibility, although it is possible that some of this high digestibility arises from digestion in the large intestine. Most studies use dairy cows cannulated in the duodenum rather than the ileum, so some of the very high postruminal starch disappearances observed when dry grains are fed might be due to fermentation in the large intestine rather than digestion in the small intestine. In addition to being energetically less efficient, fermentation of starch in the large intestine results in a loss of microbial nitrogen in feces, although the volatile fatty acids (VFA) produced are available for absorption and use by the cow.

Digestion and absorption of starch in the small intestine occurs in three phases: 1) pancreatic α-amylase initiates starch breakdown in the duodenum, 2) absorption occurs at the brush border membrane through the action of the brush border carbohydrases, and 3) glucose is transported out of the intestinal lumen and into portal circulation (Huntington 2006). There is some debate over whether any of these three phases limits intestinal digestion. However, there is clear evidence that physicochemical characteristics of grain particles limits intestinal starch digestion (Oba and Allen 2003). For example, digestion in the rumen and the small intestine of whole grains and coarsely cracked grains is limited by physical limitations (surface area, resistant hull) that restrict access to starch. While the limits to intestinal digestion are uncertain, it is clear that intestinal digestibility of starch is extremely variable among sources.

Factors Affecting Ruminal Starch Availability

Grain Source

Cereal grains are the main source of starch in the cow's diet, although cereal grain silages can also contribute significantly to starch intake (Table 1). Corn, sorghum and wheat are generally higher in starch content than barley and oats, but starch content of all grains is highly variable depending upon genotype and agronomic growing conditions.

Table 1. Starch content of some feeds and rate of starch degradation in vitro for ground samples (adapted from Herrera-Saldana et al. 1990 and Huntington 1997)

Feed source	Starch Content (% DM)	In Vitro Starch Degradation	
		Degradation at 60 min, %	Rate of degradation from 0 to 60 min, %/h
Grain			
Wheat	67 - 77	24.2	23.5
Oats	52 -69	28.0	15.1
Barley	55 - 65	18.1	8.8
Corn	72 - 78	13.1	6.4
Sorghum	68 - 78	9.4	3.1
Forages			
Corn silage, 32% grain	22		
Corn silage, 50% grain	35		

The structure and morphology of the various grains determine their inherent susceptibility to ruminal digestion. For example, barley is much more rapidly digested in the rumen than corn (Table 1). Low ruminal degradation of corn is due to the protein matrix in the horny endosperm, which is fairly resistant to digestion by ruminal microorganisms (McAllister et al. 1990). In contrast, the protein matrix in barley is rapidly digested by ruminal microorganisms once the pericarp is broken during processing (Beauchemin et al. 1994).

The inherent differences in the digestibility of barley and corn are evident in a study in which we fed dairy cows a diet containing 60% concentrate based on either steam-rolled corn or steam-rolled barley (Yang et al. 1997a,b). Dry matter intake (DMI) was similar for both groups, but starch intake was higher for cows fed corn because of its higher starch content (Table 2). Ruminal digestibility of barley starch was much higher than that of corn, and as a result, cows fed barley digested 4.9 kg/d of starch in the rumen vs 3.2 kg/d for cows fed corn. Because of the high ruminal starch digestibility of barley, its total tract digestibility was also high. In the case of corn, low ruminal starch digestibility was partially compensated for by high post-ruminal digestion, but not entirely. Consequently, total tract digestibility of corn starch trended to be lower than that of barley.

While there are inherent differences among the types of cereal grains in terms of their ruminal digestibilities, processing can alter site of digestion of all cereal grains. For example, corn can be processed such that its ruminal fermentability is similar to that of barley. Consequently, the concerns regarding the potential increased risk of acidosis with increased ruminal digestibility apply to all processed cereal grains.

Table 2. A comparison of steam-rolled barley and steam-rolled corn fed to dairy cows (Yang et al. 1997a,b).

Variable	Barley	Corn
DMI, kg/d	22.4	23.0
Starch intake, kg/d	7.1	9.0
Starch digestion		
Rumen (true), % of fed	68.6 a	35.3 b
Intestine, % of entering	78.0	71.8
Total tract, % of fed	93.2	84.5
Microbial nitrogen synthesis, g/d	286 a	237 b
Total tract organic matter digestibility, %	75.6	74.8

a,b ($P < 0.05$)

Grain Processing

Whole cereal grains require processing to improve their nutritive value, but grains differ in their response to processing. Generally, the intent of grain processing is to optimize starch availability in the rumen by obtaining a balance between maximizing starch fermentation in the rumen and avoiding digestive disturbances.

Firkins et al. (2001) summarized the published literature on the effects of processing corn for dairy cows (Table 3). Ruminal digestibility was highest for high-moisture corn, followed by steam-flaking, dry grinding, and then coarse cracking or dry-rolling. Total tract digestibility of starch followed the same general pattern. While low ruminal digestion of starch is partially compensated for by post-ruminal digestion, the compensatory digestion is not always sufficient to avoid a reduction in total tract digestion. Thus, maximizing ruminal digestion of starch maximizes total tract digestion of starch.

Table 3. A literature summary of the apparent digestibilities (% of intake) of different grain sources fed to dairy cows (from Firkins et al. 2001). The means are adjusted to remove the variation due to experiment, differences in DMI, and diet composition.

Grain	Starch		Fiber		OM	Microbial N synthesis (g/d)
	Rumen	TT	Rumen	TT	TT	
Corn						
Dry, cracked or rolled	44.6	85.0	48.1	52.0	66.6	276
Dry, ground	52.3	90.7	44.9	49.0	67.8	257
Steam-rolled		88.8		49.8	67.2	
Steam-flaked	56.9	94.2	41.9	48.2	68.6	296
High-moisture rolled	86.8	94.2	47.1	50.0	71.9	236
High-moisture, ground		98.8		50.4	73.9	
Barley, dry or steam-rolled	71.2	95.8	37.6	40.4	66.7	299

Dry-rolling and grinding

Methods such as grinding or dry-rolling crack the fibrous hull and/or pericarp to permit access of the rumen microorganisms to the internal structures (McAllister et al. 1990).
Callison et al. (2001) examined the effect of grinding size of corn for dairy cows (Table 4). The corn was coarsely, medium, or finely ground or steam-rolled (density of 0.53 kg/L). Decreasing the particle size of ground corn increased ruminal digestibility of non-structural carbohydrates (NSC, mostly starch), which corresponded to increased total tract digestibility of NSC. They concluded that corn should be finely ground to maximize total tract organic matter digestibility or steam-processed to densities less than 0.53 kg/L for maximal starch digestibility.

Table 4. Effects of corn processing on site of digestion in dairy cows (from Callison et al. 2001)

Variable	Ground Corn Fine	Medium	Coarse	Steam-rolled corn
NSC digestion				
Rumen (true), % of intake	87.0	46.5	49.8	62.1
Small intestine, % of entering	65.2	79.1	66.4	62.3
Large intestine, % of entering	82.2	51.2	56.3	46.1
Total tract, % of intake	98.0	92.2	91.3	89.3
Total tract OM digestibility, %	77.2	74.6	73.9	74.2
Milk yield, kg/d	25.0	25.4	25.0	24.6
Fat, %	3.57	3.58	3.50	3.24
Energy-corrected milk/DMI	1.38	1.43	1.33	1.31

Steam-rolling and stream-flaking

In addition to removing physical barriers and increasing the surface area, the application of heat and moisture through steam-rolling (grain steamed for < 15 min) and especially steam-flaking (grain steamed for > 30 min), causes gelatinization and swelling of the starch and increases the rate of enzymatic starch digestion (Mathison et al. 1991). In addition, applying moisture before rolling permits greater control over the resulting kernel thickness and reduces the fines and dustiness of the grain compared to dry-rolling.

In the Callison et al. (2001) study ruminal digestion of steam-rolled grain was intermediate between fine and medium ground grain (Table 4). In general, the ruminal digestibility of steam-rolled corn depends upon the degree of flatness of the kernel following processing. In that study, post-ruminal digestion was lower for steam-rolled grain than for ground grain, thus there was no advantage of steam-rolling over grinding.

The degree of steam-rolling is also very important for efficient utilization of barley (Table 5). In our studies, increasing the flatness of barley kernels during steam-rolling to a processing index (PI; measured as volume weight after processing as a proportion of volume weight before processing) of 64% increased milk yield due to increased DMI and digestibility (Yang et al. 2000). However, further processing of the grain caused milk production to decline as a result of a decline in DMI due to subacute ruminal acidosis. In another study (Yang et al. 2001a,b), the increase in DMI and starch digestibility with increased processing to PI = 60 was negated by a decrease in fiber digestion. These studies indicate that barley grain for dairy cows should be processed to a PI of 65 to maximize digestion, but barley should not be over processed (PI < 60) due to the increased the risk of acidosis.

Table 5. Effects of degree of processing of steam-rolled barley fed to dairy cows (Yang et al. 2000).

	Processing			
Variable	Coarse	Medium	Medium-flat	Flat
Processing index[1]	81	73	64	55
DMI, kg/d	18.7	21.4	21.7	20.1
Starch digestion				
Rumen, % of fed	61.0	70.3	70.5	70.7
Intestine, % of entering	39.2	47.5	78.8	75.9
Total tract, % of fed	78.0	84.1	93.6	92.9
Total tract OM digestibility, %	62.4	63.9	70.3	69.8
Microbial N synthesis, g/d	207	287	295	275
Mean rumen pH	6.16	5.97	5.97	5.96
Hours pH < 5.8	3.7	6.1	9.0	10.6

[1]Processing index is the volume weight before/after processing × 100.

Steam-flaking is superior to steam-rolling or dry-rolling for corn and sorghum (Theurer et al. 1999), but for barley, there are few advantages of steam-flaking over steam-rolling (Fiems et al. 1990; Plascencia et al. 1998). In a summary of the literature on steam-flaking and steam-rolling of corn and sorghum for dairy cows (Theurer et al. 1999), steam-flaking of corn compared to dry-rolling of corn consistently improved milk production (about 2 kg/d) and milk protein yield. These results were due to increased proportion of dietary starch fermented in the rumen, increased microbial protein flow to the duodenum, and increased total tract starch digestion (Table 6).

Table 6. Effects of steam-rolling (644 g/L) and steam-flaking of corn and sorghum on apparent digestibility and microbial protein synthesis (from Theurer et al 1999).

	Corn		Sorghum	
	Steam-rolling	Steam-flaking	Steam-rolling	Steam-flaking
Starch digestion				
Rumen, % of fed	35 a	52 b	54 a	76 b
Intestine, % of entering	61 a	93 b	74 a	90 b
Total tract, % of fed	77.5 a	96.6 b	88.7 a	97.9 b
Microbial protein synthesis, kg/d	1.04	1.23	2.10	2.33

Potential Increase in Total Tract Digestibility of Feed

Both source of grain and processing affect the ruminal digestibility of starch, and in general, increasing the ruminal digestion of starch increases total tract digestibility of starch. This concept is illustrated in Fig. 1 for corn grain, where ruminal starch digestibility was increased by processing: dry cracked or rolled; dry ground; steam-flaked; and high-moisture rolled. Increased total tract digestibility of starch increased total digestibility of OM, despite negative effects on NDF digestibility (Fig. 1). Similar relationships exist for other cereal grains, such as barley.

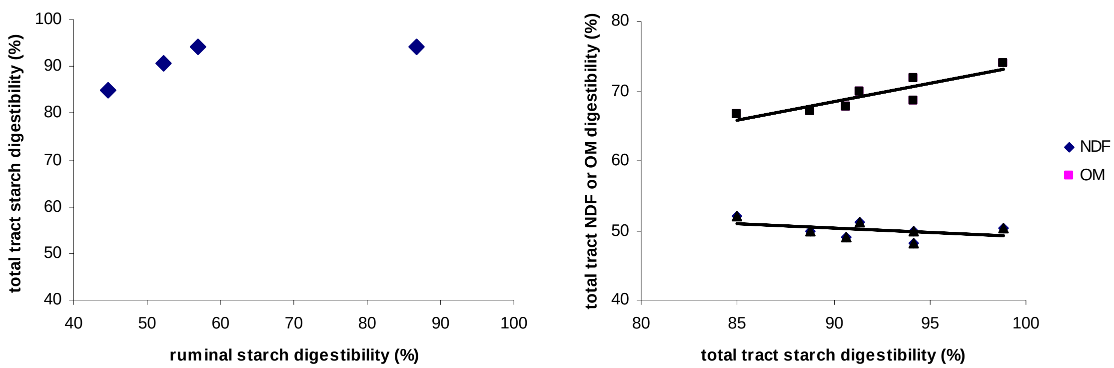

Fig. 1. Relationships between ruminal and total tract digestibility of starch (left-hand side) and relationship between total tract digestibility of starch and total tract digerstibility of NDF or organic matter. Data are from Firkins et al. (2001) and are means for processed corn grain.

Potential Increase in Microbial Protein Synthesis

Increasing the ruminal digestibility of starch has the potential to increase the flow of microbial protein (MP) to the duodenum. The amount of MP synthesized in the rumen is largely driven by the quantity of carbohydrate fermented in the rumen (Russell 1998), once the requirement for ruminally degradable protein is met. Higher ruminal digestion of barley compared with corn accounts for the generally higher MPS associated with barley diets (Table 2). In the study in which we examined flake thickness of steam-rolled barley, MPS increased with increasing processing up to medium-flat, but MPS decreased thereafter because of the decrease in DMI due to acidosis (Table 6). In the summary by Firkins et al. (2001), MPS was highest for steam-flaked corn, intermediate for dry, ground corn, and lowest for high moisture corn (Table 3). Higher MPS for steam-flaked grains compared with ground corn was due to higher ruminal digestion of starch. The relatively low MPS for high moisture grains is a notable exception to the general relationship between ruminal degradation and MPS.

Increased ruminal digestion of starch is expected to increase MPS, except if the increase in ruminal starch digestion causes subacute ruminal acidosis. Low rumen pH (i.e., pH < 5.8) decreases fiber digestion, and thus increased ruminal starch digestion is partially or entirely offset by decreased fiber digestion. Microbial protein synthesis is not increased if the supply of OM fermented in the rumen is not changed. Low rumen pH also reduces the efficiency of MCP synthesis, measured as the grams of MP per gram of ruminally available energy (Fig. 2). Efficiency of MCP synthesis is a function of the energy used by the microbes for maintenance and growth (Hespell 1979). A decrease in microbial efficiency can offset the increase in yield due to increased ruminal starch digestion, with MPS remaining unchanged.

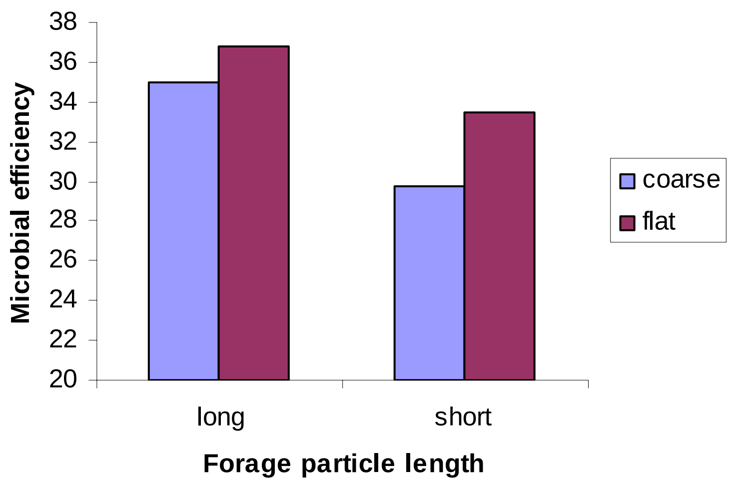

Fig. 2. Effects of forage particle length on microbial efficiency (g microbial N synthesized/g organic mater fermented in the rumen) measured in dairy cows fed coarse or flat steam-rolled barley (Yang et al. xxxx).

Potential Decrease in Rumen pH and Fiber Digestion

As the amount of starch digested in the rumen increases, ruminal pH decreases and the risk of ruminal acidosis increases. For example, in the study in which we compared steam-rolled corn and steam-rolled barley (Table 2), cows fed barley tended to have a ruminal pH that was about 0.2 units lower than for cows fed corn for most of the day, because starch digestion within the rumen was greater for barley than corn (Yang et al. 1997, Fig. 3). A similar effect of ruminal starch digestion on ruminal pH is shown in Fig. 4 for dairy cows fed high moisture corn or dry cracked corn (Krause et al. 2002). Even though particle size of the forage was coarse, rumen pH was lower for cows fed high moisture corn because of its higher fermentability.

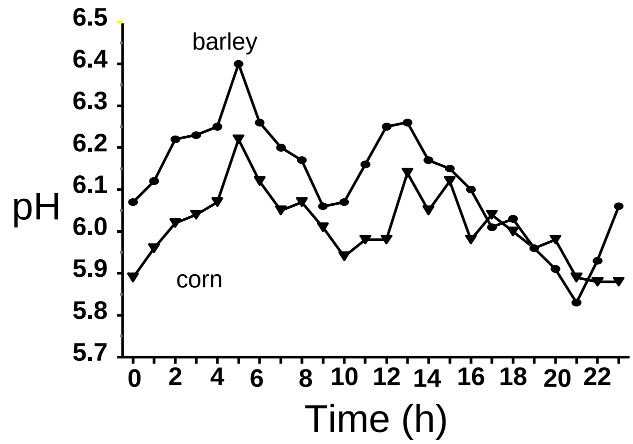

Fig. 3. Ruminal pH fed dairy cows fed steam-rolled barley or steam-rolled corn (Yang et al. 1997). Cows were fed a TMR at 0600, 1500, and 1800 h.

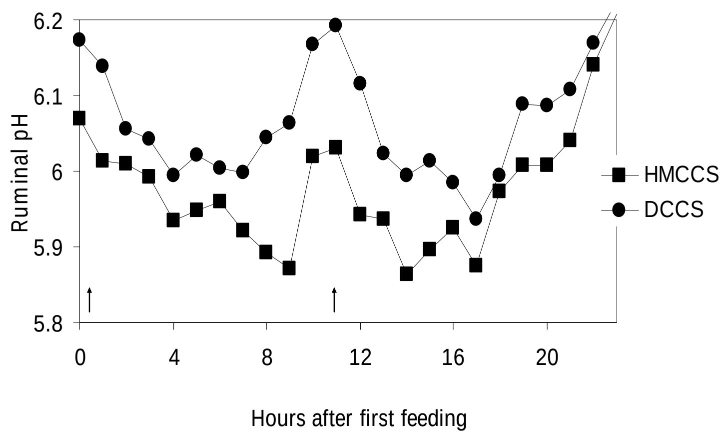

Fig. 3. Ruminal pH of dairy cows fed high moisture corn (HMC) versus cracked shelled corn (DC). The forage was coarsely chopped (CS) corn silage (Krause et al. 2002).

Low rumen pH due to increased ruminal digestion of starch decreases ruminal NDF digestiblity (Firkins et al. 2001). A decrease in ruminal NDF digestibility negates some of the improvement in starch digestibility, but the overall effect on total tract digestion of organic matter depends on the magnitude of the decrease in NDF digestion. Therefore, when formulating diets for increased ruminal starch digestion, it is essential to supply adequate physically effective fiber to minimize the incidence of ruminal acidosis.

Preventing ruminal acidosis requires a balance between the production of VFA and the neutralization/removal of VFA. If the rumen availability of starch is high, then diets need to be formulated to supply sufficient forage, of adequate particle length. Particle length of forages and the amount of forage fiber in the diet can have a significant impact on rumen pH through the provision of salivary buffers. In addition, long forage fiber creates a floating mat in the rumen, which stimulates reticuloruminal contractions. Fiber is more slowly digested than starch, so including fiber in the diet balances the increased rate of starch digestion in the rumen.

When more highly fermentable sources of grain are used (e.g., ground and flatly rolled barley, flaked corn, finely ground corn, high moisture corn), we recommend a minimum of 21 to 23% NDF from forages, if the forage is coarsely chopped (i.e., > 75% of the forage DM retained on the Penn State Particle Separator with two sieves). When forage particle size is fine, the physically effective fiber content of the diet can be increased by increasing the NDF content of the diet and/or by increasing the physically effectiveness of the forage. In addition to providing adequate fiber, good feedbunk management is critical. In particular, adequate bunk space is required to reduce competition, TMR rather than component feeding is required, abrupt changes in diet composition should be avoided, and consistent timing and quantity of feed delivery should be implemented.

Balancing the Pros and Cons: When and Where to Expect Production Responses

Increasing ruminal digestion of starch can increase milk production through increased total tract digestibility of feed and increased MPS, if acidosis is avoided. Thus, the key to attaining production responses by increasing starch fermentability is formulating diets to avoid acidosis. Production responses to increased ruminal starch digestion are greatest for higher forage diets, and diets that exceed the minimum requirement for physically effective fiber. For sources of starch that are rapidly available in the rumen, such as finely ground corn, flaked corn, high moisture corn, and finely rolled barley, improvements in starch digestibility will be offset by reduced fiber digestibility, unless the concentration of physically effective fiber in the diet is sufficient to prevent acidosis.

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