High grain diets for dairy cattle

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Summary

Continued improvements in the genetic potential of dairy cattle for milk production increase the need for maximal energy and protein availability from the diet. Grain is fed to increase the nutrient density of the diet, meet these increased needs for protein and energy, and increase the efficiency of milk production.

Starch is the primary energy component of grains, and is considered the primary driver of microbial protein synthesis in the rumen. Understanding starch digestion is the key to optimizing protein and energy supply to the cow, and to improving the efficiency and effectiveness of high grain diets. This paper reviews studies on starch digestion in the rumen, small intestine, and large intestine of ruminants; the effect of starch digestibility on performance of dairy cows; and the animal health implications and some practical aspects of feeding high grain diets to dairy cows.

Keywords: dairy cows, grain diets, starch digestion, rumen, intestines, milk

Starch digestion in the rumen

In the ruminant, the majority of starch in the diet is fermented to volatile fatty acids in the rumen. Rumen fermentation varies with type of grain as well as conservation or processing method, and this variation can greatly affect animal performance. Optimal levels of starch in the diet, and rumen fermentability of that starch depend on animal and dietary factors.

Methods of increasing rumen starch fermentation

The extent of rumen fermentation of starch is determined by the rate at which starch is fermented and its retention time in the rumen, both of which vary with species and physiological status of animal, grain type, grain genotype, growing conditions, and physical and chemical processing method (Table 1; Herrera–Saldana *et al.* 1990b; Nocek *et al.* 1991; Huntington, 1997). Herrera–Saldana *et al.* (1990b) compared rates of starch digestion of five cereal grains with *in vitro* and *in situ* methods. When processed similarly, oats had the fastest rate of starch digestion, followed by wheat, then barley, then corn, and finally sorghum.

In vivo rumen digestion of starch in various grains follows the patterns indicated by *in vitro* and *in situ* methods. In a comparison of sorghum–, corn–, and barley–based diets containing approximately 82% grain (Spicer *et al.* 1986), the rumen digestion of sorghum (75.2%) was significantly less than that of corn (83.7%) or barley (87.7%). In lactating dairy cow rations, *in vivo* digestion was much greater with barley diets than ground corn diets (77.4 vs 48.6%, $P<0.01$; McCarthy *et al.* 1989), and with barley than sorghum diets (80 vs 49%, $P<0.05$; Herrera–Saldana *et al.* 1989).

Sorghum (milo) generally has the lowest whole tract starch digestibility among cereal grains due to a hard peripheral endosperm layer which is resistant to digestion (Rooney *et al.* 1986). Waxy sorghums (cultivars whose starch is primarily amylopectin with little amylose) have consistently higher feeding value than normal sorghums and amylopectin content is positively related to starch digestibility (Rooney *et al.* 1986), but higher digestibilities of waxy cultivars may also be due to other characteristics such as less peripheral endosperm, larger starch granules within the peripheral endosperm, and different structure of the protein coat (Kotarski *et al.* 1992).

Within a grain type, dry and wet processing methods are used to alter digestibility of grains fed to ruminants. Most methods increase both rate of starch fermentation and rumen starch digestibility. Grains with lower rumen digestibilities when unprocessed, such as sorghum, seem to respond to processing to the greatest extent (Theurer, 1986).

Dry processing methods include grinding, dry rolling or cracking, popping, extruding, micronizing, roasting, and pelleting. These break the outer coat of the grain to allow access of rumen microorganisms and enzymes. Reducing particle size by cracking or grinding significantly increases the rate of starch digestion

(McAllister *et al.* 1993), but also increases rate of passage from the rumen (Galyean *et al.* 1981; Ewing *et al.* 1986). Rate of passage is affected by animal characteristics and level of intake, and increased rate of passage decreases extent of digestion in the rumen. Fine grinding may, therefore, have less effect on *in vivo* rumen starch digestibility for animals with higher levels of intake, such as dairy cattle in early lactation, than for dry cows or dairy cattle in late lactation. In beef steers on high corn diets, increased rate of passage has been observed with steam flaked grains as well as with finely ground corn (Turner *et al.* 1995). The effect of grain processing on rate of passage in lactating cows has not been evaluated.

Wet processing methods include the application of heat and/or moisture, such as soaking, steam rolling, steam processing and flaking, exploding, pressure cooking, and high moisture fermentation of early harvested or reconstituted grains. Interactions of heat, moisture, and pressure increase susceptibility of the starch to enzymatic attack and digestion by breaking down the endosperm structure, disrupting the protein matrix encapsulating starch granules in the endosperm, and gelatinizing the normally semi–crystalline starch granules (Kotarski *et al.* 1992). High moisture ensiling of early harvested or reconstituted grains increases the proportion of starch digested in the rumen of dairy cows (68 vs 78%; $P<0.05$; Aldrich *et al.* 1993). Steam flaking sorghum for dairy rations also consistently increases rumen starch digestion compared to dry ground or dry rolled sorghum (Poore *et al.* 1993a; Oliveira *et al.* 1995). Consistent increases in rumen starch digestion in lactating cows have also been observed for steam flaked corn compared to dry rolled corn (Plascencia *et al.* 1996). In steam flaked cereal grains, decreased density (incremental processing) of the flake increases rate of starch digestion (Nocek *et al.* 1991; Plascencia *et al.* 1996).

Other factors that may influence rumen starch digestion include rumen protozoa (Mendoza *et al.* 1993), level of dry matter and starch intake (Russell *et al.* 1981b; Brink *et al.* 1985), and grain cultivar (Wester *et al.* 1992; Ladely *et al.* 1995). Protozoa reduce rate of starch digestion in the rumen through ingestion of starch–digesting bacteria, and ingestion of starch granules and sugars, and defaunation of sheep has been shown to increase rumen starch digestibility (Mendoza *et al.* 1993). Level of starch intake affects starch digestion: two studies demonstrated that increased corn in steer diets increased its digestion in the rumen (Russell *et al.* 1981b; Brink *et al.* 1985). Repeatable differences in *in vitro* starch disappearance have been observed among sorghum (Wester *et al.* 1992) and among corn grain (Ladely *et al.* 1995).

Starch digestion in the small and large intestine

While most starch in ruminant diets is fermented to VFA in the rumen, in high producing dairy cattle fed high grain diets, large quantities of dietary starch may escape rumen digestion and become available for digestion, fermentation, and absorption from the small

Table 1 Starch content and rumen starch digestibility of cereal grains commonly fed to dairy cows (Herrera–Saldana *et al.* 1990b; Huntington1997).

Grain	Percent starch, ± SD	Processing method	Rumen digestibility, percent of intake
Wheat	70.3 ± 2.9	Dry rolled	88.3
		Steam rolled	88.1
Barley	64.3 ± 3.3	Dry rolled	80.7 ± 3.9
		Steam rolled	84.6
Oats	58.1 ± 4.3	Dry rolled	92.7
		Steam rolled	94.0
Corn	76 ± 1.8	Dry rolled	76.2 ± 7.9
		Steam flaked	84.8 ± 4.1
		Steam rolled	72.1
		High moisture	89.9
		Ground	49.5
Sorghum	71.3± 2.7	Dry rolled	59.8 ± 12.0
		Steam flaked	78.4
		High moisture ground	73.2
		Ground	70.0

and large intestine. Owens *et al.* (1986) observed that in 40 experiments with cattle, between 18 and 42% of dietary starch from corn and sorghum passed from the rumen intact. Higher starch intakes may promote rapid rates of passage from the rumen, causing a 'washout' of grain from the rumen to the lower tract (Huntington, 1994). Recent studies with lactating dairy cows indicate that from 1 kg to nearly 5 kg of starch may disappear post–ruminally in cows on high starch diets (McCarthy *et al.* 1989; Herrera–Saldana *et al.* 1990a; Aldrich *et al.* 1993; Poore *et al.* 1993a; Oliveira *et al.* 1995; Plascencia *et al.* 1996; Knowlton *et al.* 1998).

Given these significant flows of starch past the rumen, understanding the potential for starch digestion in the small and large intestine is important in predicting nutrient availability to the animal. Few studies with ruminants report starch flow at both the duodenum and the ileum, so partitioning starch digestion in the small intestine from fermentation in the large intestine is generally not possible.

Small intestinal starch digestion

Starch that escapes the rumen must be digested and absorbed in the lower tract to be of benefit to the cow, and the capacity of the ruminant small intestine for digestion of starch and the absorption of glucose may be limited. In general, increased flow of starch to the small intestine increases the quantity of starch digested, but decreases its digestibility there (Karr *et al.* 1966; Little *et al.* 1968; Kreikemeier *et al.* 1991). In steers fed wheat or sorghum based diets (Axe *et al.* 1987) duodenal starch flows were 518 and 1387 g/d, respectively. Small intestinal starch disappearance was 493 and 867 g/d, and small intestinal starch digestibility was 95% and 63% of that flowing into the small intestine. When Kreikemeier *et al.* (1991) infused raw corn starch to the abomasum of ilealy cannulated steers at 0, 20, 40 and 60 g/h into the abomasum of steers cannulated at the ileum, intestinal starch disappearance increased quadratically, with disappearance beginning to level off and starch flow past the ileum accelerating at the highest level of infusion (Kreikemeier *et al.* 1991).

Starch in grains treated with heat and moisture to gelatinize the starch may be more digestible in the small intestine than that in dry grains. In lactating cows fed dry or high moisture corn, duodenal starch flows averaged 3108 and 1358 g/d respectively (Figure 1; Knowlton *et al.* 1998). Despite the much lower duodenal starch flow, disappearance of starch in the small intestine was much greater on the high moisture corn diets (836 g/d; 58% of duodenal starch flow) than on dry ground corn diets (412 g/d; 9% of duodenal flow).

The infusion study of Kreikemeier *et al.* (1991) supports the suggestion that gelatinization of starch with heat and moisture increases its susceptibility to digestion in the small intestine. Infusion of similar levels of corn dextrin (starch partially hydrolyzed to destroy the granular structure) caused a linear increase in starch disappearance, suggesting that the crystalline structure of the raw corn starch inhibits small intestinal digestion in some way. At the highest levels of infusion, 55% of the infused raw corn starch and 79% of the infused dextrin disappeared (Kreikemeier *et al.* 1991). Starch granules in grain have a protective protein matrix surrounding them, so their digestibility in the small intestine is usually lower than the digestibility of purified starch or dextrin.

In addition to the amount of starch flowing past the duodenum and its structure, protein status of the animal may affect small intestinal starch digestion. Increased flow of undegraded intake protein (UIP) to the small intestine appears to increase the digestion of starch there. In steers fed barley or corn based diets, small intestinal starch disappearance was 92 g/d for barley and 328 g/d for corn. Within the corn based diets, supplementation with corn gluten meal instead of soybean meal, which increased UIP, increased starch disappearance (Taniguchi *et al.* 1994). Digestibility as a percent of duodenal flow was numerically but not significantly higher for the corn–corn gluten meal treatment than for the other three. One interpretation is

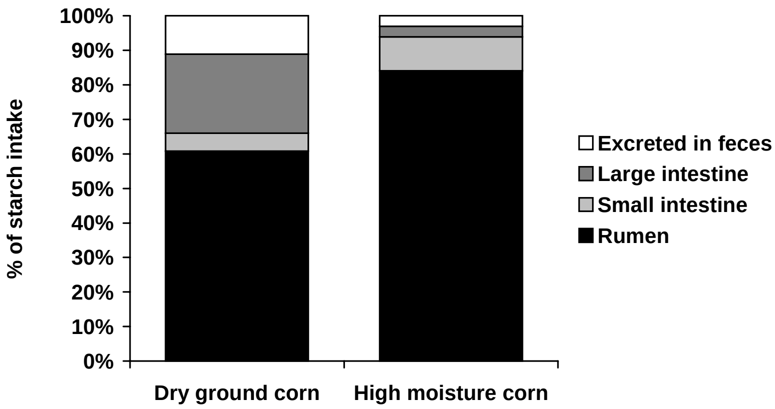

Figure 1 Site of starch digestion in six lactating cows fed dry or high moisture corn (Knowlton *et al.* 1998).

that protein source interacts with carbohydrate supply to influence small intestinal starch digestibility. Supporting this interpretation is the observation that net glucose absorption from the digestive tract was greater in steers with starch and casein infused to the abomasum than in steers with starch infused to the abomasum and casein infused to the rumen (33 vs 16 mmol/h; $P<0.05$; Taniguchi *et al.* 1994).

Starch fermentation in the large intestine

With large quantities of starch bypassing the rumen in lactating cows on high starch diets, and some limitation of small intestinal starch digestion, there may be a significant amount of starch being fermented in the large intestine. The pathways of digestion in the large intestine are similar to those in the rumen, with VFA, methane, CO_2, and microbial biomass as endproducts; volatile fatty acids can be absorbed and utilized, but microbial protein produced there is not absorbed (Armstrong *et al.* 1979). Ørskov *et al.* (1970) reported that up to 138 g of the 300 g of starch infused to the caecum of sheep fed grass hay disappeared, indicating limited but substantial capacity for fermentation in the large intestine. Increased viable counts of bacteria in caecal fluid collected from the infused sheep, and increased nitrogen excretion with increasing starch infused to the caecum, clearly indicated increased microbial nitrogen synthesis and subsequent loss of that nitrogen to the faeces.

Steers fed increasing levels of corn had an increasing proportion of starch disappear from the large intestine (Karr *et al.* 1966). Up to 11% of total starch digested on the 80% corn diet was digested in the large intestine. In steers on sorghum diets 280 g starch/d (>10% of starch intake) disappeard from the large intestine (Axe *et al.* 1987), and steers on corn based diets 109 g starch/d was digested in the large intestine. This is nearly 10% of starch intake, and apparent total tract nitrogen digestibility was depressed (Taniguchi *et al.* 1994) indicating increased microbial fermentation in the large intestine.

In high producing dairy cows, few data on disappearance of starch from the large intestine are available, but starch intakes and passage rates are high. Given the apparent limits to small intestinal starch digestion, starch flow to and fermentation in the large intestine is likely significant, increasing nitrogen losses on these diets. In one study, lactating cows fed dry ground corn had much greater duodenal and ileal starch flows (3109 and 2696 g/d) than cows fed high moisture corn (1358 and 523 g/d, Figure 1; Knowlton *et al.* 1998). Small intestinal disappearance of starch in cows fed the dry ground corn was low, but in the large intestine, more than 1800 g/d of starch disappeared; 23% of the starch in the dry ground corn diet disappeared from the large intestine. Faecal nitrogen excretion increased by 11% in cows fed dry ground corn compared with those fed high moisture corn.

Starch digestibility and animal performance

Milk yield

Although we can manipulate rumen starch digestion fairly easily, the effect on milk yield varies. Increased milk yield with increased rumen available starch was observed in early lactation cows fed barley in place of sorghum (Herrera–Saldana *et al.* 1989), fed steam flaked sorghum instead of dry rolled (Moore *et al.* 1992; Poore *et al.* 1993b), or fed ground corn instead of cracked corn (Knowlton *et al.* 1996a). Similar increases in milk yield were observed in mid–lactation cows fed corn ground more finely (Moe *et al.* 1976), fed steam flaked sorghum in place of dry rolled sorghum (Chen *et al.* 1994; Chen *et al.* 1995), fed high moisture shell corn in place of dry shell corn (McCaffree *et al.* 1968), and fed steam flaked corn instead of dry rolled (Plascencia *et al.* 1996). However diets with increased ruminally degraded starch did not affect milk or FCM yields in other studies (Clark *et al.* 1972; Clark *et al.* 1973; Bilodeau *et al.* 1989; Grings *et al.* 1992; Oliveira *et al.* 1993; Mitzner *et al.* 1994; Oliveira *et al.* 1995). Milk and FCM yields were decreased with higher ruminally degraded starch in early lactation cows fed barley instead of corn (McCarthy *et al.* 1989), fed dry rolled barley versus dry ground corn (Casper *et al.* 1990), fed high moisture shell corn in place of dry ear corn (Aldrich *et al.* 1993), and in mid–lactation cows fed untreated barley instead of the more slowly digested ammoniated barley (Robinson *et al.* 1989).

Feed intake

Decreased dry matter intake (DMI) with more rapidly fermented starch sources has been observed in early lactation cows fed barley instead of corn, (McCarthy *et al.* 1989; Casper *et al.* 1990), fed steam flaked sorghum in place of dry rolled sorghum (Moore *et al.* 1992), and fed high moisture shell corn in place of dry ear corn (Aldrich *et al.* 1993) or dry shell corn (McCaffree *et al.* 1968; Clark *et al.* 1972). Similar reductions in DMI with increased rumen starch digestion were observed in mid–lactation cows fed dry ground corn versus dry ground sorghum (Mitzner *et al.* 1994) and fed steam flaked sorghum in place of dry rolled sorghum (Oliveira *et al.* 1993). Other studies, however, showed no change in intake with altered rumen digestion of starch (Clark *et al.* 1973; Bilodeau *et al.* 1989; Herrera–Saldana *et al.* 1989; Grings *et al.* 1992; Poore *et al.* 1993b; Chen *et al.* 1995; Oliveira *et al.* 1995; Knowlton *et al.* 1996a). In contrast, in one study with sorghum and one with corn, steam flaking has been shown to improve intake relative to dry rolling (Chen *et al.* 1994; Plascencia *et al.* 1996), and grinding corn increased intake in mid lactation cows relative to whole corn (Moe *et al.* 1976).

The improvement in DMI observed in some studies with diets with less ruminally degraded starch may be due to a number of factors. One possible mechanism is less rapid post–prandial accumulation of acid in the rumen and a minimization of rumen pH fluctuation. Excess fermentation of starch to volatile fatty acids in the rumen may overwhelm the buffering and absorptive capacity of the rumen, leading to fluctuations in rumen pH that may decrease DMI in the high producing dairy cow (Robinson *et al.* 1988; McCarthy *et al.* 1989).

If fluctuation in rumen pH is an appropriate explanation for the decreased DMI with increased rumen digestion of starch observed in some studies, it is more likely to be a factor with higher starch intakes, lower fibre concentrations, or more variation in forage quality. Six studies have been reported with lactating cows where both DMI and rumen starch digestion have been measured. Three studies indicate no effect of rumen starch digestion on DMI, and the quantity of starch digested in the rumen on the high digestibility diet ranged from 4700 to 5400 g/d (Herrera–Saldana *et al.* 1990a; Poore *et al.* 1993a; Oliveira *et al.* 1995). The two studies indicating depression in intakes had rumen starch digestion in excess of 6500 g/d.

One study (Plascencia *et al.* 1996) indicated an increase in DMI with steam flaked corn compared to dry rolled corn when rumen starch digestion was relatively low (2700 vs 1900 g/d). The increase in DMI in this and other studies with ground or steam flaked corn (Moe *et al.* 1976; Chen *et al.* 1994) may also be explained by changes in rate of passage observed with these processing methods (Galyean *et al.* 1981; Ewing *et al.* 1986; Turner *et al.* 1995). If bulk fill is limiting intake in these cows, increased rates of digestion and passage with ground or steam flaked grain may allow higher intakes.

Another reason for the disparity in research results is the type of grain that is processed. As previously observed, when cows are fed grains with lower intrinsic rumen fermentability (e.g. sorghum), responses to processing are greater. Of the studies indicating improvements in milk yield with increased rumen degradable starch, most are with sorghum grain that compare steam flaking to dry rolling (Moore *et al.* 1992; Poore *et al.* 1993b; Chen *et al.* 1994; Chen *et al.* 1995).

Milk protein production

Increasing the energy content of the diet by increasing grain feeding generally results in an increase in milk protein concentration (Poore *et al.* 1993b; Chen *et al.* 1994) that can be attributed to greater microbial protein synthesis promoted by an increased supply of ruminally fermented carbohydrates. Recent research suggests that increased feeding of fermentable starch may also increase milk protein concentration through changes in whole body glucose and insulin response (McGuire *et al.* 1995). Increased digestion of starch in the rumen generally increases supplies of propionate and other glucose precursors; increased synthesis of glucose elicits an insulin response, and both effects can increase milk protein concentration.

Animal health and productivity

Increasing grain content of diets increases concerns about the health and productivity of animals fed these diets. Rumen acidosis (acute and sub–acute), impaired fibre digestion, and milk fat depression dominate any discussion of the effect of high grain diets on the health of dairy cows.

Rumen acidosis

Acute acidosis is primarily associated with the accumulation of lactate, and is more commonly observed in beef cattle on 80–100% grain diets than in lactating dairy cows. Lactate is a major fermentation end product of starch on these very high starch diets. Lactate has a pKa of 3.86 while acetate, propionate and butyrate have pKa's around 4.8. When rumen pH declines, lactate may cause a more dramatic decline in pH than the VFA due to this lower pKa.

Cattle abruptly switched to high concentrate diets often accumulate lactate in the rumen, which decreases rumen pH and causes acute acidosis (Slyter, 1976). Lactate production increases because large quantities of readily fermentable carbohydrate are available. Normally, lactate production is not advantageous in the rumen, because each sugar fermented to lactate yields only 2 ATP. When carbohydrate is limiting, production of other VFA is more efficient. When carbohydrate is plentiful, however, microbes capable of rapid growth which often produce lactate are favoured (Russell *et al.* 1981a). The decline in rumen pH to below 5 caused by lactate accumulation then creates a niche for *Lactobacillus* species, lactate producers which are resistant to low rumen pH (Slyter, 1976; Russell *et al.* 1983; Russell *et al.* 1985).

The extent of lactate accumulation equation is also affected by the activity of lactate utilizers which may take time to adjust to changes in diet and become less competitive as pH declines. That these will adjust to high grain diets is supported by feedlot data that show cattle developing mild acidosis and going off feed before adapting to a high concentrate diet (Kunkle *et al.* 1976). A decline in rumen pH to below 5, or an increase in liquid dilution rate makes most lactate utilizers uncompetitive and creates a niche for *Lactobacillus* (Slyter, 1976; Russell *et al.* 1983; Russell *et al.* 1985). Lactate, with pKa 3.86, is likely to affect rumen pH when it accumulates, and this spiraling effect of increasing lactate production and decreasing pH contributes to the development of acute acidosis.

Symptoms and consequences of acute acidosis may include dullness, diarrhoea, hyperventilation, dehydration, inhibited muscular activity of the rumen wall, parakeratosis (a thickening of the rumen wall which decreases VFA absorption), reduced salivation, reduced intestinal motility, damage to the rumen, damage to the liver, and death.

Sub–acute acidosis is more common in lactating cows than is acute acidosis, and is primarily associated with production of VFA in excess of the rumen's capacity for absorption and buffering. Consequences of sub–acute acidosis are reduced feed intake, laminitis, and reduced milk yield (Slyter, 1976; Nagaraja *et al.* 1985).

Diets high in ruminally degraded starch increase total ruminal VFA concentrations (McCarthy *et al.* 1989; Knowlton *et al.* 1998). Cows fed ground corn diets had mean rumen pH similar to cows fed cracked corn diets (Knowlton *et al.* 1996b), but the range in pH within a day was increased with ground corn. Reductions in rumen pH have been demonstrated in animals fed ground and pelleted barley as compared to those fed whole barley (Ørskov *et al.* 1975; Ørskov *et al.* 1978) or NaOH treated barley (Ørskov *et al.* 1978). Treatment of high moisture barley with increasing levels of ammonia to decrease digestibility reduced the rate of pH decline following meals in lactating cows (Robinson *et al.* 1989).

A reduction in feed intake is often observed with increased rumen starch digestion and increased VFA concentration. One explanation is that low rumen pH reduces fibre digestibility (see below), which would increase the retention of fibre in the rumen and affect feed intake because of limitations associated with rumen fill. Alternatively, the rapid accumulation of acid, *per se*, may decrease intake. Treatment of grass silage with sodium bicarbonate increased silage pH from 4.0 to 5.4, and increased subsequent DMI of sheep and cattle by 9.7 to 20.7% (McLeod *et al.* 1970). Addition of lactic acid to grass silage reduced pH from 5.4 to 3.8, and reduced subsequent DMI of sheep by 22%. Receptors sensitive to changes in pH have been isolated in the rumen epithelium (Baile and Della–Fera, 1981). As rumen pH falls below 5 or 5.5, feed intake is most likely depressed because of rumen stasis associated with acute acidosis. Rumen pH is not likely to be a physiological controller of intake, but rather a primary cause of reduced intake in pathological situations.

Chemical treatments of grain have been used to reduce rumen starch digestion in an attempt to avoid acidosis while retaining the benefits of high grain diets. Treatment of whole barley with anhydrous ammonia decreased rumen organic matter digestion in beef cattle by 11% but increased small intestinal digestion with no effect of treatment on total tract digestibility (Mandell *et al.* 1988). Similar effects were found with formaldehyde treatment of ground corn which reduced rumen starch digestion by up to 41% with no reduction in whole tract starch digestibility (Fluharty *et al.* 1989; Oke *et al.* 1991). Adoption of these practices in the field has been limited because of human health and safety concerns.

Fibre digestion on high grain diets

Decreased fibre digestibility is typically observed with diets containing rapidly digested starch. The rapid accumulation of acids reduces rumen pH which impairs the growth of cellulolytic bacteria and slows forage cell wall digestion (McCarthy *et al.* 1989; Grant, 1994). Impaired fibre digestion may lead to reductions in feed intake.

Exceptions have been noted: in studies where grains with low digestibility (e.g. sorghum) were processed, increases in rumen fibre digestibility were reported (Poore *et al.* 1993a; Chen *et al.* 1994). These apparently contradictory observations are best explained as the result of making poorly available starch more available, consequently improving overall microbial activity in the rumen. Depression in fibre digestibility is the more common result of increasing ruminally fermented starch, especially when relatively available starch sources (dried ground corn or barley) are processed to increase further the availability (by steam flaking or steam rolling).

Milk fat depression on high grain diets

Increasing grain content of the diet usually decreases milk fat concentration, a change commonly explained by changes in rumen fermentation (McClymont 1995). Diets containing high amounts of ruminally degraded starch typically increase rumen propionate concentrations and decrease acetate to propionate ratio (McCarthy *et al.* 1989; Moore *et al.* 1992; Aldrich *et al.* 1993; Oliveira *et al.* 1993; Knowlton *et al.* 1996b; Plascencia *et al.* 1996). Propionate is a precursor for the synthesis of glucose by the liver, while acetate is a precursor for the synthesis of fat by the mammary gland and body tissues. The decrease in milk fat with high grain diets has, therefore, been classically explained by a general shift from lipogenesis to gluconeogenesis. Recent research, however, suggests that the depression in milk fat may also be caused by an accumulation of trans–fatty acids in the rumen that is a consequence of a low rumen pH with high grain diets (Gaynor *et al.* 1995; Kalscheur *et al.* 1997b; Kalscheur *et al.* 1997a).

Practical aspects of feeding high grain diets

Total mixed rations vs meal feeding and frequency of feeding

The intake of concentrates reduces the intake of forage and the forage:concentrate ratio. This reduced intake of forages may be due to limited capacity for feed intake, limitations on total energy required, and/or effects of grain feeding on rumen fermentation. Despite decreases in forage intake, total feed intake and intake of energy usually increases with grain supplementation. The response to starch supplementation depends on the physiological state of the cow, the type of forage and grains fed, and how the grain is provided (Reynolds *et al.* 1997).

Addition of grain may be through a total mixed ration (TMR), or by allowing *ad libitum* intake of forages with a fixed quantity of grain. When starchy grains (corn, oats) are added to the diet using the latter approach, forage intake is typically reduced by 0.4–0.5 kg/kg of grain added (Sutton *et al.* 1996; Reynolds *et al.* 1997). More frequent feeding of silage minimizes this reduction. When addition of grain was through a TMR instead of being fed separately, silage consumption decreased by just 0.3 kg/kg concentrate fed (Reynolds *et al.* 1997).

Several aspects of TMR feeding explain this difference in response to grain addition. When grain is included in a TMR, cows are less able to discriminate between feed ingredients, preventing selective consumption of grain in preference to forage. In addition, patterns of rumen fermentation are different in cows fed a TMR from those in cows fed grain and forage separately. When grain is given separately, the fermentation of large quantities of starch in a short period of time can lead to production of VFA that exceeds the capacity of the rumen for absorption and buffering. Sutton *et al.* (1986) demonstrated that feeding a TMR in two meals caused much greater fluctuation in rumen pH, and decreased minimum rumen pH, compared with feeding the same TMR in 24 hourly meals. When hay and grain were given separately in this series of low–forage experiments (Sutton *et al.* 1986), more frequent feeding of grain (5–6 times a day) resulted in a smaller depression in milk fat than when it was provided twice daily, and reduced circulating NEFA. In another series of experiments, lactate concentrations peaked after feeding, and these concentrations were higher in cows fed 12 kg of grain once a day than in cows fed the same total amount of grain in two or four feeds (Malestein *et al.* 1981).

Buffers

Substances such as sodium bicarbonate, magnesium oxide, or calcium carbonate are commonly added to high grain diets as ‘buffers’ to alleviate digestive upsets, minimize depression in fibre digestibility, and maintain milk fat content. It was thought that these compounds worked by neutralizing the acids produced during rumen fermentation. More recent research indicates, however, that there is no relationship between the inclusion of buffers and rumen pH, rumen fluid characteristics, or milk fat concentration (Russell *et al.* 1993). The benefit observed in the field from use of these compounds is not, therefore, due to any buffering action. Instead, it appears that they increase water intake, increase dilution of rumen fluid, and increase the passage of starch from the rumen. Sodium chloride (common salt) has the same effects on water consumption and passage rate and is, therefore, equally effective in alleviating digestive upsets.

Conclusions

Grains vary in starch content and in rumen availability of starch. Within a grain type, grinding, steam rolling or flaking, and ensiling grains at high moisture are techniques commonly used to increase rumen starch digestibility. Processing increases rate of starch digestion in the rumen, but the extent of digestion *in vivo* is affected by mastication and rate of passage as well as rate of digestion.

While the majority of starch in the diet is fermented in the rumen, duodenal starch flow may routinely exceed 1.5–2 kg/d in cows fed high starch diets. Disappearance of starch from the small intestine increases with increasing flow of starch from the same source, but digestibility as a percent of that presented decreases. Different sources of starch may differ in degree of gelatinization and accessibility to intestinal enzymes, and very high duodenal starch flows may yield very little small intestinal starch disappearance. With these diets, fermentation in the large intestine of glucose to VFA may be significant.

Increased rumen starch digestion generally increases the ratio of acetate to propionate in rumen fluid, and increases rumen VFA concentration. Rumen pH fluctuation (range within a day, or post–prandial rate of decline) generally increases with increased rumen starch digestion. There appears to be an upper limit for rumen starch digestion, beyond which the buffering and absorptive capacity of the rumen is overwhelmed and DMI is impaired. This limit varies with fibre concentration, feed particle size, and digestibility, and animal factors such as stage of lactation and parity. Milk yield responses to increased rumen starch digestion seem to be determined by the response in intake to treatment, and by the grain type. Processing of poorly digested grains such as sorghum to increase their digestibility nearly always results in increased milk yield.

Total feed intake is usually increased by addition of starchy grains to an all forage diet, but forage consumption decreases. The increase in total intake is greater with TMR feeding systems than when forages and grains are given separately, and is greater with more frequent feeding than with twice daily feeding. Decreased forage consumption increases the risk of sub–acute acidosis, impaired fibre digestibility, and decreased milk fat concentration.

As genetic improvement continues in dairy cattle, nutrition must improve to meet the increased need of the cow for energy and protein. Improved understanding of starch digestion allows optimization of protein and energy supplies, and is necessary to identify management techniques to maximize the benefits of high grain diets.

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