Effects of Physically Effective Fiber on Digestion and Milk Production by Dairy Cows Fed Diets Based on Corn Silage*

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ABSTRACT

Effects of physically effective (pe) neutral detergent fiber (NDF) content of dairy cow diets on nutrient intakes, site and extent of digestion, microbial protein synthesis and milk production were evaluated in a double 3×3 Latin square design using 6 lactating dairy cows with ruminal and duodenal cannulas. During each of 3 periods, cows were offered 1 of 3 diets that were chemically similar but varied in peNDF content (high, medium, and low) by altering corn silage particle length. The peNDF contents were determined using the Penn State Particle Separator and were 11.5, 10.3, and 8.9%, for the high, medium, and low diets, respectively, and the physical effectiveness factors for the long, medium, and fine silages were 84.1, 72.6, and 67.2%, respectively. Increased forage particle length increased intake of peNDF but did not affect intakes of nutrients including dry matter, NDF, starch, and nitrogen. Except for starch, apparent digestibilities of nutrients in the total tract were linearly increased with increasing dietary peNDF. Fiber digestion was affected by dietary peNDF to a greater extent than were the other nutrients. However, increased digestibility due to increased dietary peNDF did not significantly improve milk production or milk composition. Increased dietary peNDF also increased numerically rumen microbial protein synthesis due to increased amount of organic matter fermented in the rumen. These results indicate that increasing the peNDF content of a corn silage based diet improves digestibility, especially digestibility of fiber, in the total tract. Dietary particle size, expressed as peNDF, is positively associated with nutrient digestibility when level of peNDF in the diet is low.

(Key words: physically effective neutral detergent fiber, digestion, milk production, dairy cow)

Abbreviation key: CS = corn silage, FPL = forage particle length, pef = physical effectiveness factor,

peNDF = physically effective NDF, PSPS = Penn State Particle Separator consisting of 2 sieves (19 and 8 mm) and a pan.

INTRODUCTION

Adequate long fiber, in a form that is physically effective, is necessary in dairy cow diets to maintain proper rumen function because long forage particles in the diet promote chewing and salivary buffer secretion, ultimately elevating rumen pH (Beauchemin, 1991). The physical effectiveness of dietary particles can affect feed intake, digestive efficiency, milk production and composition, and health of the cow (Allen, 1997).

The concept of physically effective fiber (peNDF) was introduced (Mertens, 1997) to relate the physical characteristics of feeds to rumen pH by assessing the effects of feed particle size on chewing activity. The term peNDF combines the physical effectiveness factor (pef) of the feed with its NDF content and can be used in diet formulation to ensure adequate particle size. The Penn State Particle Separator (PSPS) is a quick and effective method that can be used on-farm (Lammers et al., 1996) to measure the pef of feeds. A number of studies have recently shown the beneficial effects of increasing chewing activity and rumen pH by increasing the peNDF content of dairy cow diets. For instance, Krause et al. (2002) reported that chewing time increased by 4.3 h/d when the pef of alfalfa silage was increased from 0.31 to 0.69. Beauchemin et al. (2003) reported that chewing activity and rumen pH were improved when peNDF contents of alfalfa forage based diets were linearly increased from 7.2 to 15.0%. Kononoff and Heinrichs (2003a) observed that chewing time per unit of DM or NDF were significantly increased with increasing peNDF intake for a corn silage (CS) diet.

The physical characteristics of feeds such as particle length can affect rumen and total tract digestibility, passage rate, and microbial protein synthesis. For example, efficiency of ruminal microbial protein synthesis and digestion of N in the rumen or in the total tract were improved with increasing forage particle length (FPL; Rode et al., 1985; Yang et al., 2002). Furthermore, fiber digestibility in the total tract was increased with increasing chop length of CS (Bal et al., 2000).

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Based on measurements using the PSPS, several studies reported that increased intake of peNDF increased milk fat content (Yang et al., 2001; Kononoff and Heinrichs, 2003b) and decreased milk protein content (Kononoff and Heinrichs, 2003b), but others did not find any effects of peNDF on milk composition (Beauchemin et al., 2003; Kononoff et al., 2003). The optimum concentration of peNDF in dairy cow diets is uncertain, as there is a paucity of information on the effects of peNDF on digestibility and milk production for a range of forages and concentrates.

The objectives of the present study were to determine the effects of increasing the peNDF concentration of a diet containing CS on feed intake, site and extent of digestion, microbial protein synthesis, and milk yield and composition in lactating dairy cows. The peNDF concentration of the diet was increased by using CS differing in particle length and the peNDF content of the diets was determined using the PSPS.

MATERIALS AND METHODS

Corn Silage

Corn silage used in the present study was obtained from a local commercial dairy farm. A corn hybrid (whole plant) (Pioneer Hi-Bred Intl., Des Moines, IA) was harvested at about 31% DM using a self-propelled forage harvester (model FX58; New Holland, New Holland, PA) set to obtain a 19.1-mm theoretical cut length with kernel processing at a 2-mm roll clearance. The chopped corn material was placed in a bunker silo, covered with black plastic, and ensiled for at least 2 mo. The silage was transported daily from the dairy farm to the Dairy Facility at the Lethbridge Research Centre during the experiment. Each day, a portion of the silage was rechopped using a small bedding chopper fitted with an 11-mm sieve to obtain silage of medium particle length. The medium particle length silage was rechopped a second time to obtain silage of fine particle length. The originally prepared silage was designated as the long particle silage.

Cows and Diets

Six lactating Holstein cows were used in an experiment to investigate effects of peNDF content of CS based diets on feed intake, digestion, microbial protein synthesis, and milk production. Three cows fitted with ruminal cannulas and 3 cows fitted with ruminal and duodenal cannulas were separately assigned to 3 × 3 Latin squares for each group of cows. The ruminal cannulas measured 10 cm in diameter and were constructed of soft plastic (Bar Diamond, Parma, ID). Duodenal cannulas were T-shaped and were placed proxi-

Table 1. Ingredients and chemical composition of the total mixed diet (DM basis).

Ingredient	%
Corn silage ¹	41.85
Barley grain, steam-rolled ¹	37.80
Corn gluten meal	0.90
Heat-treated canola meal (Alberta Gold)	5.86
Soybean meal	9.92
Beet molasses	0.68
Calcium carbonate	0.63
Dicalcium phosphorus	0.41
Vitamin-mineral mix ²	1.13
Canola oil	0.68
Binding agent (Aka)	0.15
Chemical composition	
DM, %	54.6
OM, % of DM	92.6
CP, % of DM	17.1
NDF, % of DM	32.6
NDF from forages, % of NDF	61.5
ADF, % of DM	15.4
Starch, % of DM	34.8
NE _L , Mcal/kg	1.70

¹Chemical composition of corn silage and barley grain (DM basis) was 93.8 and 90.5% for OM; 46.5 and 23.2% for NDF; 26.6 and 6.3% for ADF; and 8.7 and 11.3% for CP, respectively.

²Contained 51.97% NaCl, 35.98% Dynamate (Pitman Moore, Inc., Mundelein, IL; 18% K, 11% Mg, 22% S, 1000 mg Fe/kg), 2% ZnSO₄·H₂O, 2.4% MnSO₄·4H₂O, 0.01% CoSO₄·6H₂O, 0.009% Na₂SeO₃, 0.012% ethylenediamine dihydroiodide, 0.8% CuSO₄·5H₂O, 680,000 IU/kg of vitamin A, 160,000 IU/kg of vitamin D, and 2000 IU/kg of vitamin E.

mal to the common bile and pancreatic duct, approximately 10 cm distal to the pylorus. Cows were housed in individual tie stalls and offered a TMR 3× daily at 0800, 1500, and 1800 h for ad libitum intake. Cows averaged 622 ± 84 kg of BW and 48 ± 25 DIM, and were cared for according to the Canadian Council on Animal Care Guidelines (Ottawa, ON, Canada).

Cows were offered 1 of 3 diets, all of which were chemically identical and contained approximately 58% concentrate and 42% CS (Table 1), but differed in peNDF level: high, medium, and low. The 3 dietary peNDF levels were obtained using CS differing in particle length: 100% long silage (high), 25% long silage + 75% medium silage (medium), and 100% fine silage (low) (Table 2). The diets were formulated using the Cornell-Penn-Miner System (CPMDairy, Version 2.23, Cornell University, Ithaca, NY; University of Pennsylvania, Kennett Square, PA; and William H. Miner Agricultural Research Institute, Chazy, NY) to supply adequate metabolizable energy and metabolizable protein for a 600-kg cow producing 35 kg of milk/d with 3.5% fat and 3.2% protein. Each period consisted of 11 d for adaptation to diets and 10 d for experimental measurements. A relatively short adaptation phase was used to minimize the difference in stage of lactation between the start and finish of the experiment. Because diets

Table 2. Particle size distribution, physical effectiveness factors (pef), and physically effective fiber (peNDF) contents of the corn silage and the diets.

Item	Particle length			SE	Effects	
	Long	Medium	Fine		Linear	Quadratic
Corn silage						
% DM retained on screens						
19.0 mm	20.6	17.8	16.5	0.9	0.01	NS
8.0 mm	63.5	54.8	50.7	1.0	0.01	NS
Pan	15.9	27.4	32.8	1.7	0.01	NS
pef, ¹ %	84.1	72.6	67.2	1.7	0.01	NS
peNDF, ² % of DM	39.0	34.1	30.9	0.9	0.01	NS
Diet						
% DM retained on screens						
19.0 mm	8.6	7.9	7.0	0.2	0.01	NS
8.0 mm	26.6	24.4	21.5	0.7	0.01	NS
Pan	64.7	67.7	71.5	0.9	0.01	NS
pef, ¹ %	35.3	32.3	28.5	0.7	0.01	NS
peNDF, ² % of DM	11.5	10.3	8.9	0.5	0.01	NS

NS = $P < 0.15$.¹pef = Determined as the proportion of DM retained by both sieves of the Penn State Particle Separator.²peNDF = Measured as the NDF content of the TMR multiplied by its pef.

differed only in particle size, and not chemical composition, a short adaptation phase was deemed acceptable.

Feed offered and orts were measured and recorded daily during the last 10 d of the period to calculate feed intake. Feed samples including CS and TMR were collected once weekly, and orts were collected daily and composited weekly for particle length and DM determination on a weekly basis. Dry matter was determined by drying samples in a forced air oven at 55°C for 48 h. Dried diet and ort samples were then composited by period. The composited samples were ground through a 1-mm diameter screen (standard model 4, Arthur Thomas Co., Philadelphia, PA) for analysis of OM, NDF, ADF, starch, and CP. Milk production was recorded daily, a.m. and p.m., and sampled on 5 consecutive days during the last 10 d of the period for milk fat, CP, and lactose content determined using an infrared analyzer (Milk-O-Scan 605, Foss Electric, Hillerød, Denmark).

Duodenal Flow and Apparent Digestion

Duodenal flow and apparent digestion of nutrients in the total tract or at the different sites of the digestive tract were determined using YbCl₃ (Rhône-Poulenc Inc., Shelton, CT) as a digesta flow marker. Ammonia ¹⁵N ([¹⁵NH₄)₂SO₄, 10.6 atom % ¹⁵N; Isotec, Miamisburg, OH) was used as a ruminal microbial marker. Marker solution was continuously infused into the rumen via the ruminal cannula using an automatic pump (model 60 rpm/7524-10, Masterflex L/S Microprocessor pump drive, Vernon Hills, IL) during the last 11 d of the period. Daily amounts infused were 2.6 g of Yb and 140 mg of ¹⁵N dissolved in 800 mL of water for each cow. Six ruminal samples were collected from 3 duodenally

cannulated cows during 3 d of collection for rumen bacterial pellet preparation. Duodenal and fecal samples were collected 4 times daily every 6 h moving ahead 2 h each day for the last 3 d of infusion. This schedule provided 12 representative samples of duodenal and fecal contents taken at 2-h intervals. A ruminal and a duodenal sample taken before marker infusion from each cow at the first period were used to determine background concentration of ¹⁵N in samples.

Ruminal samples were processed immediately to separate ruminal bacteria. The samples were squeezed through 4 layers of cheesecloth and the particles obtained by squeezing were blended (400 g of particles plus 400 mL of 0.9% NaCl) in a Waring blender (Waring Products Division, New Hartford, CT) for 1 min and then squeezed through 4 layers of cheesecloth. Filtrates from squeezed and strained homogenate were mixed and centrifuged (800 × *g* for 10 min at 4°C) to remove protozoa and feed particles. The supernatant was then centrifuged (27,000 × *g* for 30 min at 4°C) to obtain a mixed ruminal bacteria pellet (Cecava et al., 1990). Bacterial pellets were accumulated by period, freeze-dried, ground using a mortar and pestle, and then further ground using a ball mill (Mixer Mill MM2000; Retsch, Haan, Germany) to a fine powder for determination of N content and ¹⁵N enrichment.

Duodenal samples were subdivided using an electric drill fitted with a shaft and propeller. Each sample was split into 3 fractions that were pooled by cow within period and retained for ammonia and cell-free ¹⁵N analysis, DM determination after oven drying at 55°C, or for chemical analysis after freeze-drying. The sample for cell-free ¹⁵N analysis was centrifuged at 27,000 × *g* for 30 min at 4°C and the supernatant was stored at

-20°C for ^{15}N determination. Fecal samples were also pooled by cow for each period, dried at 55°C, and ground through a 1-mm screen (standard model 4) for chemical analyses.

Chemical Analyses

Feed DM was determined by oven drying at 55°C for 48 h. Analytical DM content of the samples was determined by drying at 135°C for 3 h (AOAC, 1990). The OM content was calculated as the difference between DM and ash contents, with ash determined by combustion at 550°C for 6 h. The NDF and ADF contents were determined using the methods described by Van Soest et al. (1991) with amylase and sodium sulfite used in the NDF procedure. Starch was determined by enzymatic hydrolysis of α -linked glucose polymers as described by Rode et al. (1999). Contents of Yb in the duodenal and fecal samples were determined using inductively coupled plasma optical emission spectroscopy according to the AOAC method (1990) modified such that no calcium chloride was used during sample digestion. Content of N in the samples was determined by flash combustion (model 1500; Carlo Erba Instruments, Milan, Italy), and enrichment of ^{15}N in the rumen bacterial and duodenal samples was analyzed with isotope ratio mass spectrometry (VG Isotech, Middlewich, England). Natural abundance of ^{15}N concentration was assumed constant at 0.3666% for all samples. The ^{15}N concentration measured in ruminal bacterial or duodenal samples collected before ^{15}N infusion was used to compensate for background ^{15}N concentration. Ammonia content of duodenal samples was determined using the method described by Weatherburn (1967) modified for using a plate reader. Particle size distributions of CS, TMR, and orts were determined using the PSPS. Physical effectiveness factors for silage, TMR, and orts were calculated as the sum of the proportions of the materials retained on the 19.0- and 8.0-mm sieves of the PSPS. The peNDF of the diets was determined by multiplying the pef of the TMR by the NDF content (DM basis) of the diet.

Calculations and Statistical Analyses

Flows of DM to the duodenum and DM excreted in feces were calculated by dividing Yb infused (grams of Yb per day) by Yb concentration (grams of Yb per kilogram of DM) in the duodenal digesta or feces, respectively. Flows of other nutrients to the duodenum or feces were calculated by multiplying DM flow by their concentration in duodenal or fecal DM. Ruminal microbial protein synthesis for each cow was estimated by the ratio of ^{15}N flow at the duodenum to ^{15}N concen-

tration of mixed ruminal bacteria. The flow of ^{15}N incorporated into the microbes in duodenal digesta was calculated as the difference between total ^{15}N flow and cell-free ^{15}N flow in the duodenum.

Data were analyzed using the mixed model procedure of SAS (Proc Mixed; SAS Institute, 1996) to account for effects of square, period within square, cow within square, and treatment. The treatment was considered a fixed effect; square, period within square, and cow within square were considered random effects. For variables of site of digestion and microbial protein synthesis, data from a single square were analyzed. In that case, the mixed model accounted for effects of period, cow, and treatment. The treatment was considered a fixed effect; period and cow were considered random effects. The estimation method was the restricted maximum likelihood (REML) and the degrees of freedom method was Kenward-Rogers. All variables were tested for linear and quadratic effects in relation to the peNDF content of the diets. Effects of the treatments were declared significant at $P < 0.05$ unless otherwise noted and trends were discussed at $P < 0.15$.

RESULTS AND DISCUSSION

Intake and Apparent Digestion in the Total Tract

Intakes of DM, fiber, and N were not significantly affected by the peNDF content of the diet (Table 3). These results are in contrast to some studies in which reducing peNDF intake by reducing FPL had positive effects on DMI and NDF intake (Schwab et al., 2002; Kononoff et al., 2003), but they are in agreement with others in which no effect was observed (Bal et al., 2000; Yang et al., 2001). However, intake of starch tended linearly ($P < 0.15$) to decrease with reduced peNDF content of the diet. Differences in intake of starch across the treatments were attributed to a particle selecting effect. Cows on all diets consumed a greater proportion of long particles than was presented to them in the TMR. Furthermore, the finer the diet, the more pronounced the effect. The proportion of long particles (i.e., those retained on the 19-mm sieve) left in the orts of the various peNDF diets (6.3, 1.7, and 0.2%, for high, medium, and low, respectively) was larger than the proportion in the original diets (8.9, 7.9, and 7.0%, for high, medium, and low, respectively), indicating selection of long forage over small particles (Figure 1). The pef of the diets were greater than the pef of the orts, and the difference between the pef of diet and orts was greatest for the low peNDF diet (34, 39, and 45% reduction for high, medium, and low, respectively) (Figure 2), indicating that relatively more particles >19.0 and >8.0 mm were consumed for cows fed the low peNDF diet.

Table 3. Effects of reducing dietary physically effective fiber (peNDF) on intake and digestibility of nutrients in the total tract of lactating dairy cows (n = 6).

Item	Dietary peNDF			SE	Effects	
	High	Medium	Low		Linear	Quadratic
Intake						
DMI, kg/d	21.1	21.0	20.3	3.8	NS	NS
DMI, % of BW	3.3	3.3	3.1	0.3	NS	NS
NDF intake, kg/d	6.6	6.5	6.1	1.2	NS	NS
NDF intake, % of BW	1.0	1.0	0.9	0.1	0.14	NS
Forage NDF intake, kg/d	4.1	4.1	3.9	0.8	NS	NS
Forage NDF intake, % of BW	0.6	0.7	0.6	0.1	NS	NS
peNDF ¹ intake, kg/d	2.5	2.3	1.9	0.5	0.01	NS
ADF, kg/d	3.2	3.4	3.2	0.6	NS	NS
Starch, kg/d	7.4	7.7	6.7	1.1	0.15	NS
N, g/d	566.1	557.3	535.1	97.9	NS	NS
BW, kg	638	637	639	68	NS	NS
Digestibility, % of intake						
DM	70.2	68.4	67.6	1.5	0.02	NS
OM	71.5	69.8	69.0	1.5	0.03	NS
NDF	47.2	43.9	37.9	2.2	0.01	NS
ADF	36.5	35.7	31.4	2.2	0.02	NS
Starch	90.8	90.6	89.7	1.8	NS	NS
N	66.4	63.9	62.5	2.9	0.02	NS

NS = $P > 0.15$.¹peNDF = Measured as the NDF content of the TMR multiplied by its pef.

Apparent digestibilities of DM, OM, NDF, ADF, and N in the total tract were linearly increased with increasing dietary peNDF (Table 3). These results are in agreement with some reports (Schwab et al., 2002; Yang et al., 2002; Kononoff and Heinrichs, 2003b) but in contrast to other findings (Yang et al., 2001; Kononoff and Heinrichs, 2003a). Lower digestibility of DM in the total tract of dairy cows fed finely vs. coarsely chopped CS was detected by Kononoff and Heinrichs (2003b), but no effect of FPL on digestibility of NDF was observed. In that study, increased DM digestibility in the total tract was attributed to increased postruminal digestibility of total nonstructural carbohydrates rather than an effect on fiber digestibility. The difference in response between our study and that of Kononoff and Heinrichs (2003b) was probably related to the differences in peNDF contents of the diets (i.e., range of 15.6 to 18.4% used by Kononoff and Heinrichs (2003b) vs. 7 to 8.9% used in the present study). It appears that whether FPL affects fiber digestibility depends upon the concentration of peNDF in the diet. For example, it was observed that fiber digestibility was reduced with reducing FPL of alfalfa silage when peNDF was reduced to a minimum of 7.2% (Yang et al., 2002), but the effect was not observed when the peNDF was reduced to 9.5% (Yang et al., 2001). Beauchemin and Yang (2003a) concluded that increasing FPL has a significant effect on increasing chewing time, but only if diets contain low levels of forage fiber or when the particle size of the TMR is fine. Increasing chewing time of low forage diets

may improve rumen pH status, and thus fiber digestibility.

Influence of dietary peNDF on digestibility in the total tract is more pronounced for fiber digestion than for starch digestion. In the case of starch, low ruminal digestion can be partly or wholly compensated for by high intestinal digestion (Yang et al., 1997; Beauchemin et al., 2001). Yang et al. (2002) reported a shift of starch digestion from the rumen to the intestine with increasing FPL such that total digestion was not affected. However, the amount of fiber that can be digested in the intestine is limited. Furthermore, increasing FPL promotes chewing activity and thus increases saliva secretion, which prevents ruminal pH from declining, especially during meal consumption (Beauchemin, 2000). In the present study, decreased digestibility due to reduced dietary peNDF was consistent with the reduction of chewing activity and ruminal pH during the eating period, and the ratio of acetate to propionate with decreasing dietary peNDF (Yang and Beauchemin, 2003), indicating that fiber digestion in the rumen was impaired when fine silage was fed.

Site and Extent of Digestion

Data for site and extent of nutrient digestion were obtained from a single 3 × 3 Latin square using 3 primiparous lactating dairy cows fitted with ruminal and duodenal cannulas. Because the power of this experimental design was limited in terms of detecting treatment dif-

Figure 1. Proportion of particles >19.0 mm for the diets and Orts determined using Penn State Particle Separator.

ferences at $P < 0.05$, trends are discussed. Thus, results must be cautiously interpreted.

Intakes of DM (17.0 kg/d) and other nutrients (Table 4) were lower than the averages for all cows (Table 3). This difference could have reflected the physiological differences between primiparous and multiparous cows or the effects of intestinal cannulation. Although not statistically significant, there was on average a 15% reduction in intake when the low peNDF diet was fed compared with the high or medium peNDF diets. It is possible that primiparous cows are more susceptible to the effects of peNDF level.

Duodenal flows were not affected by the treatments, whereas, microbial OM flow was numerically decreased ($P > 0.15$) with reducing dietary peNDF (Table 4). The decrease in microbial OM flow was consistent with the amount of OM fermented in the rumen, which was also linearly decreased ($P > 0.15$) with reduced dietary peNDF. Digestibilities of OM and fiber in the rumen were consistent with the values reported by McCarthy et al. (1989) and Overton et al. (1995) for using diets containing CS and barley grain. However, starch digestibility in the rumen was lower than that observed by those workers, but was in agreement with our previous findings for barley-based diets (Yang et al., 2001, 2002). Ruminant digestibility of fiber and starch was similar across treatments. Reduced amount of fiber digested in

the rumen resulting from reduced particle length of the diet (i.e., 1.81 kg of NDF/d for high vs. 1.48 kg of NDF/d for low) was mostly the result of decreased DMI.

Digestibility in the intestine was not affected by dietary peNDF (Table 4), and the values were consistent with other reports (Overton et al., 1995; Yang et al., 2002). Numerical effects of reducing dietary peNDF on decreasing NDF digestibility in the intestine agreed with our previous studies (Yang et al., 2001, 2002). Shifting starch digestion from the rumen to the intestine with long forage may have contributed to increased intestinal fiber digestion in the previous studies. Increased intestinal starch digestibility provides more energy for bacterial fermentation in the large intestine, which could lead to increased fiber digestion. Similarly, in the current study, the amount of starch digested in the intestine was numerically higher for cows fed the high (2.23 kg/d) and medium (2.67 kg/d) diets than for those fed the low peNDF diet (1.68 kg/d).

Effects of dietary peNDF on digestibility in the total tract observed for the duodenally cannulated cows (Table 4) were consistent with the effects reported for all cows (Table 3). Decreasing dietary peNDF tended ($P < 0.09$) to reduce NDF digestibility in the total tract (Table 4). The mechanism whereby total tract fiber digestibility was reduced is not clear, as treatments had no effect on ruminal or intestinal digestibility. However, a numerical reduction in intestinal digestibility was observed for cows fed the low peNDF diet. Reducing peNDF content of the diets also caused a small, likely insignificant, quadratic ($P < 0.06$) and linear ($P < 0.13$) reduction in starch digestibility in the total tract.

Intake and duodenal flows of total or nonammonia N were not affected by the diet (Table 5). However, the flow of rumen undegradable N (measured as the feed plus endogenous fraction) was quadratically increased ($P < 0.12$) with decreasing dietary peNDF. Thus, the proportion of rumen undegradable N in the total N intake was significantly higher for the medium or low diets than for the high peNDF diet, and as a result, rumen N digestibility and flow of microbial N were numerically lower for the medium or low diet than for the high peNDF diet. Lower microbial production resulted from lower nutrient availability to the rumen microbes as rumen fermented OM was 1.7 or 2.1 kg/d less for the medium or low diets, respectively, compared with the high peNDF diet. Digestibility of N in the intestine tended to numerically increase ($P > 0.15$) with decreasing particle length of CS, which resulted in overcoming the decrease in ruminal digestibility of N. Thus, total tract digestibility of N was not significantly different among treatments. The decreases of rumen N digestibility and microbial protein yield with reducing dietary peNDF were in agreement with previous re-

Figure 2. Physically effective factors for the diets and Orts.

Table 4. Effects of reducing dietary physically effective fiber (peNDF) on intake, duodenal flow, and site and extent of digestion of nutrients in lactating dairy cows (n = 3).

Item	Dietary peNDF			SE	Effects	
	High	Medium	Low		Linear	Quadratic
Intake, kg/d						
DM	17.9	17.7	15.5	2.4	NS	NS
OM	16.5	16.4	14.4	2.2	NS	NS
NDF	5.4	5.5	4.6	0.7	NS	NS
ADF	2.6	2.8	2.4	0.4	NS	NS
Starch	6.4	6.6	5.1	0.9	NS	NS
Duodenal flow, kg/d						
OM						
Total	9.0	10.0	8.2	1.9	NS	NS
Microbial	2.2	1.7	1.6	0.5	NS	NS
NDF	3.6	2.9	3.2	0.8	NS	NS
ADF	1.6	1.8	1.6	0.4	NS	NS
Starch	2.8	3.2	2.4	0.9	NS	NS
RFOM, ¹ kg/d	9.8	8.1	7.7	1.4	NS	NS
Digestibility, % of intake						
Rumen						
OM (truly)	59.3	50.0	54.5	6.3	NS	NS
NDF	33.6	30.8	32.2	7.3	NS	NS
ADF	39.2	38.2	34.5	6.6	NS	NS
Starch	55.9	51.9	56.0	11.8	NS	NS
Intestine						
OM	24.4	29.8	23.6	5.9	NS	NS
NDF	12.5	12.9	4.7	6.8	NS	NS
ADF	2.4	3.0	5.1	7.2	NS	NS
Starch	34.8	40.4	33.0	10.3	NS	NS
Total						
OM	70.3	69.3	67.9	2.4	NS	NS
NDF	46.1	43.7	36.9	4.1	0.09	NS
ADF	41.7	41.4	39.6	3.4	NS	NS
Starch	90.7	92.2	88.9	2.4	0.13	0.06

NS = $P > 0.15$.¹RFOM = Organic matter that was truly fermented in the rumen calculated by correcting for microbial OM.

ports (Yang et al., 2002) that rumen N digestibility and microbial efficiency were lowest, 41.9% and 18.2 g of N/kg of rumen fermented OM, respectively, when part of the forage fed was ground alfalfa hay.

Milk Production and Composition

Milk yield and 4% FCM were similar across treatments, averaging 37.8 and 31.0 kg/d, respectively (Table 6). These results agree with other studies in which CS of varying particle length was fed to dairy cows (Schwab et al., 2002; Kononoff and Heinrichs, 2003b). Failure to observe effects of dietary peNDF on milk production contrasts with the effect of increasing dietary peNDF on increasing digestibility of DM, NDF, and N in the total tract. Milk yield is a variable that is less sensitive to the effects of dietary peNDF than other variables, such as digestibility. In fact, average milk yield was 1.6 kg/d (4.3%) lower for cows fed the low diet than the average milk yield for cows fed the other 2 diets. However, the variability of milk production among cows within a diet was very high (CV =

16.4%), thus, we were unable to detect statistical significance among diets. Thus, it is not surprising that the published results on the effects of particle size on milk production are conflicting. The variability in milk production among cows was partly because both multiparous and primiparous cows were used, cows were cannulated, and experimental periods were short. No responses of milk production to increased digestibility with increasing particle length of CS were observed by others (Bal et al., 2000; Kononoff et al., 2003).

Milk component (fat, protein, and lactose) percentages and yields were not affected by dietary peNDF content (Table 6). However, in this study, milk fat content averaged 2.88, 2.67, and 3.02% for high, medium, and low peNDF diets, respectively, and was below normal values for this herd, such that the ratio of milk fat to protein content was very low (1:1). Low milk fat content was consistent with low mean rumen pH (5.50) and low ratio of acetate to propionate (range of 1.7 to 2.0) (Yang and Beauchemin, 2003), which reflected the low intake of forage NDF and low ruminal NDF digestibility (Table 4). Although dietary NDF from forage in

Table 5. Effects of reducing dietary physically effective fiber (peNDF) on intake and metabolism of N in the digestive tract of lactating dairy cows (n = 3).

Item	Dietary peNDF			SE	Effects	
	High	Medium	Low		Linear	Quadratic
Intake, g/d	484.6	473.1	412.2	68.8	NS	NS
Flow to duodenum						
Total						
g/d	416.8	455.8	374.9	78.4	NS	NS
% of intake	86.0	94.5	93.6	8.2	NS	NS
NAN ¹						
g/d	409.8	447.4	366.6	77.7	NS	NS
% of intake	84.6	92.7	91.6	8.4	NS	NS
Feed + endogenous						
g/d	179.1	276.2	211.6	50.1	NS	0.12
% of intake	37.7	56.7	55.0	8.4	0.03	NS
Microbial						
g/d	230.7	171.2	155.0	55.4	NS	NS
% of intake	46.9	36.0	36.6	8.5	NS	NS
g/kg of RFOM ²	22.3	22.2	19.2	3.9	NS	NS
Digestibility						
Ruminal (truly), %	62.3	43.3	45.0	8.3	0.13	NS
Postruminal						
% of intake	49.9	56.1	54.5	5.6	NS	NS
% of flow to duodenum	57.6	58.6	57.1	3.8	NS	NS
Total tract						
% of intake	63.9	61.6	60.9	5.0	NS	NS

NS = $P > 0.15$.¹NAN = Nonammonia N.²RFOM = Ruminal fermented OM.

the current study met the minimum requirement (19%) of NRC (2001), it was below the recommendation (21 to 23%) of Beauchemin and Yang (2003a,b) for barley-based diets. Furthermore, the starch content (34.8%) of the diets exceeded their maximum recommendation (33%). It is well documented that diets that provide large quantities of readily available carbohydrates with limited peNDF cause milk fat depression as a result of changes in ruminal processes (Bauman and Griinari, 2001). Similar milk protein content across treatments

probably resulted from similar starch digestibility in the total tract because milk protein is positively correlated with dietary energy (Grieve et al., 1986).

CONCLUSIONS

Increased FPL of CS linearly increased intake of peNDF, but generally did not affect intake of nutrients. Digestibility in the total tract, especially for fiber digestion, was improved with increasing the intake of peNDF. These results indicate that increasing intake of peNDF can increase ruminal fiber digestion by improving rumen function and intestinal fiber digestion. Furthermore, increasing peNDF intake tended to improve microbial synthesis in the rumen due to an increased amount of OM fermented in the rumen. Because the cows used in this research were in midlactation, increasing peNDF content of the diet did not affect feed intake, milk production, or milk composition. However, for cows in early lactation, improved fiber digestion in the rumen because of increased intake of physically effective fiber is expected to increase energy balance and performance of cows. Dietary particle size, expressed as peNDF, was positively associated with nutrient digestibility. Further studies are needed to determine the optimum concentration of peNDF in dairy cow diets in terms of maintaining healthy rumen function and maximizing nutrient digestion.

Table 6. Effects of reducing dietary physically effective fiber (peNDF) on milk production and composition (n = 6).

Item	Dietary peNDF				Effects	
	High	Medium	Low	SE	Linear	Quadratic
Milk yield, kg/d						
Actual	38.0	38.7	36.7	6.2	NS	NS
4% FCM	31.5	30.9	30.6	4.7	NS	NS
Milk fat						
%	2.88	2.67	3.02	0.24	NS	NS
kg/d	1.09	1.03	1.06	0.15	NS	NS
Milk protein						
%	2.85	2.90	3.12	0.13	NS	NS
kg/d	1.08	1.12	1.12	0.20	NS	NS
Milk lactose						
%	4.68	4.67	4.51	0.18	NS	NS
kg/d	1.77	1.81	1.69	0.29	NS	NS
Milk/DMI	1.83	1.90	1.83	0.15	NS	NS

NS = $P > 0.15$.

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REFERENCES

- Allen, M. S. 1997. Relationship between fermentation acid production in the rumen and the requirement for physically effective fiber. *J. Dairy Sci.* 80:1447–1462.
- Association of Official Analytical Chemists. 1990. *Official Methods of Analysis*. Vol. I. 15th ed. AOAC, Arlington, VA.
- Bal, M. A., R. D. Shaver, A. J. Jirovec, K. J. Shinnars, and J. G. Coors. 2000. Crop processing and chop length of corn silage: Effects on intake, digestion, and milk production by dairy cows. *J. Dairy Sci.* 83:1264–1273.
- Bauman, D. E., and J. M. Griinari. 2001. Regulation and nutritional manipulation of milk fat: Low-fat milk syndrome. *Livest. Prod. Sci.* 70:15–29.
- Beauchemin, K. A. 1991. Ingestion and mastication of feed. *Vet. Clin. North Am. Food Anim. Pract.* 7:439–463.
- Beauchemin, K. A. 2000. Managing rumen fermentation in barley based diets: Balance between high production and acidosis. *Adv. Dairy Technol.* 12:109–125.
- Beauchemin, K. A., and W. Z. Yang. 2003a. Forage: How much do dairy cows need in a time of scarcity? *Adv. Dairy Technol.* 15:261–274.
- Beauchemin, K. A., and W. Z. Yang. 2003b. Importance of physically effective fiber in dairy diets. Pages 113–124 in *Proc. 24th Western Nutrition Conference*, Winnipeg, MB, Canada.
- Beauchemin, K. A., W. Z. Yang, and L. M. Rode. 2001. Effects of barley grain processing on the site and extent of digestion of beef feedlot finishing diets. *J. Anim. Sci.* 79:1925–1936.
- Beauchemin, K. A., W. Z. Yang, and L. M. Rode. 2003. Effects of particle size of alfalfa-based dairy cow diets on chewing activity, rumen fermentation, and milk production. *J. Dairy Sci.* 86:630–643.
- Cecava, M. J., N. R. Merchen, L. C. Gay, and L. L. Berger. 1990. Composition of ruminal bacteria harvested from steers as influenced by dietary energy level, feeding frequency, and isolation techniques. *J. Dairy Sci.* 73:2480–2488.
- Grieve, D. G., S. Korver, Y. S. Rijpkema, and G. Hof. 1986. Relationship between milk composition and some nutritional parameters in early lactation. *Livest. Prod. Sci.* 14:239–254.
- Kononoff, P. J., and A. J. Heinrichs. 2003a. The effect of reducing alfalfa haylage particle size on cows in early lactation. *J. Dairy Sci.* 86:1445–1457.
- Kononoff, P. J., and A. J. Heinrichs. 2003b. The effect of corn silage particle size and cottonseed hulls on cows in early lactation. *J. Dairy Sci.* 86:2438–2451.
- Kononoff, P. J., A. J. Heinrichs, and H. A. Lehman. 2003. The effect of corn silage particle size on eating behavior, chewing activities, and rumen fermentation in lactating dairy cows. *J. Dairy Sci.* 86:3343–3353.
- Krause, K. M., D. K. Combs, and K. A. Beauchemin. 2002. Effects of forage particle size and grain fermentability in midlactation cows. II. Ruminal pH and chewing activity. *J. Dairy Sci.* 85:1947–1957.
- Lammers, B. P., D. R. Buckmaster, and A. J. Heinrichs. 1996. A simple method for the analysis of particle sizes of forage and total mixed rations. *J. Dairy Sci.* 79:922–928.
- McCarthy, R. D., Jr., T. H. Klusmeyer, J. L. Vicini, J. H. Clark, and D. R. Nelson. 1989. Effects of source of protein and carbohydrate on ruminal fermentation and passage of nutrients to the small intestine of lactating cows. *J. Dairy Sci.* 72:2002–2016.
- Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. *J. Dairy Sci.* 80:1463–1481.
- Overton, T. R., M. R. Cameron, J. P. Elliott, J. H. Clark, and D. R. Nelson. 1995. Ruminal fermentation and passage of nutrients to the duodenum of lactating cows fed mixtures of corn and barley. *J. Dairy Sci.* 78:1981–1998.
- Rode, L. M., D. C. Weakley, and L. D. Satter. 1985. Effect of forage amount and particle size in diets of lactating dairy cows on site of digestion and microbial protein synthesis. *Can. J. Anim. Sci.* 65:101–111.
- Rode, L. M., W. Z. Yang, and K. A. Beauchemin. 1999. Fibrolytic enzyme supplements for dairy cows in early lactation. *J. Dairy Sci.* 82:2121–2126.
- SAS Institute. 1996. *SAS7 User's Guide. Statistics*. Version 7 ed. SAS Inst., Inc., Cary, NC.
- Schwab, E. C., R. D. Shaver, K. J. Shinnars, J. G. Lauer, and J. G. Coors. 2002. Processing and chop length effects in brown-midrib corn silage on intake, digestion, and milk production by dairy cows. *J. Dairy Sci.* 85:613–623.
- Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber and non-starch polysaccharide in relation to animal nutrition. *J. Dairy Sci.* 74:3583–3597.
- Weatherburn, M. W. 1967. Phenol-hypochlorite reaction for determination of ammonia. *Anal. Chem.* 39:971–974.
- Yang, W. Z., and K. A. Beauchemin. 2003. Effects of physically effective NDF on rumen fermentation and nutrient digestion of dairy cows fed diets based on barley or corn silages. *J. Anim. Sci.* 81(Suppl. 1)/*J. Dairy Sci.* 86(Suppl. 1) 1:340.
- Yang, W. Z., K. A. Beauchemin, B. Farr, and L. M. Rode. 1997. Comparison of hull-less barley, barley or corn for lactating cows: Effects on extent of digestion and milk production. *J. Dairy Sci.* 80:2475–2486.
- Yang, W. Z., K. A. Beauchemin, and L. M. Rode. 2001. Effects of grain processing, forage to concentrate ratio, and forage particle size on rumen pH and digestion by dairy cows. *J. Dairy Sci.* 84:2203–2216.
- Yang, W. Z., K. A. Beauchemin, and L. M. Rode. 2002. Effects of particle size of alfalfa-based dairy cow diets on site and extent of digestion. *J. Dairy Sci.* 85:1958–1968.