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Effects of Grain Processing, Forage to Concentrate Ratio, and Forage Particle Size on Rumen pH and Digestion by Dairy Cows[1]

W. Z. Yang, K. A. Beauchemin, and L. M. Rode[2]
Livestock Sciences Section, Research Centre
Agriculture and Agri-Food Canada,
Lethbridge, AB, T1J 4B1, Canada

ABSTRACT

Dietary factors that alter the intake of effective fiber were evaluated for their effects on rumen fermentation, digestion, and milk production using a double 4 × 4 quasi-Latin square design with a 2^3 factorial arrangement of treatments. The dietary factors were extent of barley grain processing, coarse (1.60 mm) or flat (1.36 mm); forage-to-concentrate (F:C) ratio, low (35:65) or high (55:45) (dry matter basis); and forage particle length, long (7.59 mm) or short (6.08 mm). Eight lactating cows with ruminal and duodenal cannulas were offered ad libitum access to a total mixed diet and milked twice daily. Dry matter intake was increased by increasing the extent of grain processing. Mean rumen pH was lower for cows fed flatly rolled barley than for cows fed coarsely rolled barley, whereas F:C ratio or forage particle size had no effect on rumen pH. Rumen pH was not correlated with effective NDF intake but tended to be correlated with digestibility of starch in the rumen. Total tract digestibilities of dry matter, organic matter, starch, and neutral detergent fiber were increased by feeding flatly rolled barley or low F:C ratio diets. Milk yield and milk protein content were higher in cows fed flatly rolled barley or low F:C ratio diets. Milk fat content tended to increase with high F:C ratio or long forage particle length but was reduced by feeding flatly rolled barley. In this study, extent of grain processing and intake of ruminal available starch were the most influential factors affecting milk production. Reducing the ratio of F:C improved total digestion and actual milk production. Forage particle length had minimal impact on digestibility and milk production.
(**Key words:** grain processing, effective fiber, digestibility, dairy cows)

Abbreviation key: eNDF = effective NDF, **eNDFf** = effective NDF factor, $\mathbf{eNDFf}_{CNCPS}$ = eNDF factor determined using the Cornell Net Carbohydrate and Protein System (version 4.0), $\mathbf{eNDFf}_{CPM}$ = eNDF factor determined using the Cornell-Penn-Miner Dairy System (version 1.0), $\mathbf{eNDF}_{CNCPS}$ = effective NDF measured as the NDF content of the TMR multiplied by $\mathbf{eNDFf}_{CNCPS}$, $\mathbf{eNDF}_{CPM}$ = effective NDF measured as the NDF content of the TMR multiplied by $\mathbf{eNDFf}_{CPM}$, **ERD** = effective ruminal degradability, **F:C** = forage to concentrate ratio, **MPL** = mean particle length, **pe** = physically effective, **pef** = physical effectiveness factor, $\mathbf{pef}_M$ = physical effectiveness factor from tabular values of chewing time, $\mathbf{pef}_{P>1.18}$ = physical effectiveness factor determined as a percent of DM remaining on a 1.18 mm screen measured using a dry sieving technique, $\mathbf{pef}_{PS}$ = physical effectiveness factor calculated as the sum of the DM proportions retained on the two sieves of the Penn State Particle Separator, **peNDF** = physically effective NDF, $\mathbf{peNDF}_M$ = physically effective NDF measured as the NDF content of the TMR multiplied by pef_M, $\mathbf{peNDF}_{P>1.18}$ = physically effective NDF measured as the NDF content of the TMR multiplied by $pef_{P>1.18}$, $\mathbf{peNDF}_{PS}$ = physically effective NDF measured as the NDF content of the TMR multiplied by pef_{PS}, **PI** = processing index (measured as volume weight of barley after processing, expressed as a percentage of its volume weight before processing), **PSPS** = Penn State Particle Separator.

INTRODUCTION

It is well recognized that dairy cows require sufficient fiber, of adequate particle length, to maintain proper rumen function. Feeding finely processed forages decreases the time spent chewing, decreases the ruminal acetate-to-propionate ratio, lowers ruminal pH, and reduces the fat content of milk (Beauchemin et al., 1994a; Grant et al., 1990). However, it is often difficult to ensure adequate long fiber in dairy cow rations because the proportion of concentrate in the diet is usually high, and high quality, finely chopped silages are used to meet the energy requirements of high production. Fur-

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Corresponding author: K. A. Beauchemin; e-mail: beauchemin@em.agr.ca.
[1]Contribution number: 387-0067.
[2]Present address: Biovance Technologies Inc., Lethbridge, AB, T1K 3J5, Canada.

thermore, the definition of adequate long fiber is not clear.

Numerous attempts have been made to describe the fiber requirements of dairy cows (Mertens, 1997; Santini et al., 1983). Currently, the NRC (1989) recommends a minimum of 25 to 28% fiber, measured as NDF, with 75% of the total dietary NDF supplied by forages. However, this approach does not account for the differing particle size of various forages or the fiber contributed by concentrate sources. Subsequently, the concept of effective NDF (**eNDF**) was adopted (NRC, 1996; Pitt et al., 1996) to describe the total ability of the feed to replace forage such that milk fat percentage is maintained. In models of feed formulation, including the Cornell Net Carbohydrate and Protein System, CPMDairy, and NRC (1996), eNDF content of the diet is used to predict ruminal pH. One possible limitation of this approach is that the fermentability of the nonfiber carbohydrate fraction, and its possible effects on rumen pH, are not accounted for in the prediction (Pitt et al., 1996). Thus, these models implicitly assume that ruminal digestion of the diet has no effect on predictions of rumen pH, which may be incorrect. For example, rumen pH is lower for cows fed barley rather than corn, even when diets contain the same proportion of eNDF, due to the more rapid, and more extensive ruminal digestion of barley (Yang et al., 1997). The usefulness of eNDF is also limited as it is impossible to measure outside of conducting a full feeding study (Armentano and Pereira, 1997).

More recently, the concept of physically effective (**pe**) fiber was introduced (Mertens, 1997) to relate the physical characteristics of feeds to rumen pH by measuring particle length or chewing activity. It was proposed that the physical effectiveness factor (**pef**) of individual feeds could be measured based on chewing activity (Mertens, 1997). As chewing time requires animal experimentation, an alternative approach to assessing the pef of feeds is to determine the proportion of the feed retained on a 1.18-mm sieve. Alternatively, the diet can be sieved into three fractions with the Penn State Particle Separator (**PSPS**) (Lammers et al., 1996) with the sum of the DM retained on the two sieves assumed to be equal to pef. It was recommended that 6 to 10% of the TMR be retained on the top screen (19-mm), 30 to 50% on the middle (8-mm), and 40 to 60% on the bottom pan (Lammers et al., 1996). Mertens (1997) recommended multiplying the pef of the diet by its NDF content to calculate physically effective NDF (**peNDF**). A minimum peNDF intake of 20% of the ration DM was recommended for lactating dairy cows.

Dietary factors that influence intake of eNDF and pe fiber of dairy cows include such factors as forage-to-concentrate ratio (**F:C**) and forage particle size (Beauchemin and Rode, 1997; Grant et al., 1990; Sarvar et al., 1992). However, there is limited information concerning the effects of these dietary factors and their interactions on rumen fermentation, or site and extent of digestion (Rode et al., 1985; Yang et al., 2000). Furthermore, it is not known whether the response to the intake of eNDF and pe fiber depends upon the fermentability of the noncarbohydrate sources in the diet. The objectives of this study were to evaluate the effects of the extent of grain processing, F:C, forage particle length, and their interactions on feed intake, rumen pH, site and extent of digestion, and performance of dairy cows. Grain processing was used as a means of altering ruminal fermentability of starch, while F:C and forage particle length were used to vary the intake of eNDF and pe fiber.

MATERIALS AND METHODS

Cows and Diets

Eight lactating Holstein cows that were surgically and permanently fitted with ruminal and duodenal cannulas were used. The ruminal cannulas measured 10 cm in diameter and were constructed of soft plastic (Bar Diamond, Parma, ID). Duodenal cannulas were constructed of plastisol, open T-shaped, and were placed proximal to the common bile and pancreatic duct, approximately 10 cm distal to the pylorus. At the start of the experiment, the cows averaged 628 ± 59 kg of BW and 134 ± 35 DIM and were housed in individual tie stalls and milked twice daily in their stalls at 0700 and 1700 h. Cows were offered a TMR three times daily at 0630, 1500, and 1800 h ad libitum. Cows were weighed at approximately 0830 h at the beginning and end of each period, and these weights were used to calculate mean BW of cows for each experimental period. Cows were cared for according to the Canadian Council on Animal Care Guidelines (Ottawa, ON, Canada).

The experimental design was a double 4 × 4 quasi-Latin square (Cochran and Cox, 1957) with a 2^3 factorial arrangement of treatments and with four 21-d periods for each square. The design used in this experiment arranged half the treatments in square 1 and the other half in square 2 such that the three-way interactions were confounded but all other effects were unconfounded. Each period consisted of 11 d of adaptation to diets and 10 d of experimental measurements consisting of milk production and composition, feed intake, ruminal pH, site and extent of digestion, and in sacco ruminal digestibility. Each period within square, cows received one of four diets, such that each cow received four of the eight diets by completion of the study.

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

	Diets	
	Low forage	High forage
Ingredients		
Alfalfa silage[1]	10.0	16.1
Barley silage[1]	17.8	28.5
Alfalfa hay[1]	7.2	10.4
Barley, steam-rolled[2]	50.2	27.6
Corn gluten meal	2.92	3.32
Blood meal	0.97	0.47
Canola meal	4.39	1.42
Soybean meal	0.97	4.75
Molasses, beet	0.97	1.42
Calcium carbonate	0.88	1.04
Dicalcium phosphorus	0.44	0.52
Monophosphorus	0.39	0.47
Vitamin-mineral mix[3]	2.38	2.58
Canola oil	0.49	1.42
Chemical		
DM	64.8	57.1
OM	91.1	89.5
CP	17.9	18.3
NDF	31.7	37.8
NDF from forages	15.1	23.5
ADF	17.4	23.9
Starch	32.9	24.1
NE_L, Mcal/kg[4]	1.66	1.59

[1]Chemical composition of alfalfa silage, barley silage, and alfalfa hay (DM basis) was 88.5, 91.8 and 90.7% for OM; 41.7, 42.4 and 45.1% for NDF; 17.8, 12.9 and 17.7% for CP, respectively. Starch content of barley silage was 24.9%.

[2]Physical characteristics of coarsely and flatly rolled barley were 75.5 and 60.2% for processing index; 1.60 and 1.36 mm for kernel thickness; 4.68 and 5.74 mm for kernel width, respectively.

[3]Contained 51.97% NaCl, 35.98% Dynamate (Pitman Moore, Inc., Mundelein, IL; 18% K, 11% Mg, 22% S, 1000 mg Fe/kg), 2% $ZnSO_4 \cdot H_2O$, 2.4% $MnSO_4 \cdot 4H_2O$, 0.01% $CoSO_4 \cdot 6H_2O$, 0.009% Na_2SeO_3, 0.012% ethylenediamine dihydroiodide, 0.8% $CuSO_4 \cdot 5H_2O$, and (per kilogram) 680,000 IU of vitamin A, 160,000 IU of vitamin D and 2000 IU of vitamin E.

[4]Estimated from NRC (1989).

The eight diets were formulated by combining three factors, each with two levels. The factors studied were: grain processing (coarse vs. flat), F:C (low vs. high), and forage particle length (long vs. short). Coarsely and flatly rolled barley was produced during the rolling process. Ratios of F:C were 35:65 and 55:45 for low and high, respectively. Long particle forage was the original forage regularly fed in the Dairy Unit at the Lethbridge Research Centre, while the short particle forage was prepared by rechopping the alfalfa silage and barley silage, and grinding the alfalfa hay through a 4-mm screen. Chemical composition differed between diets with low and high F:C. The low F:C diets consisted of approximately 10% alfalfa silage, 18% barley silage, 7% alfalfa hay, and 65% concentrate, and high F:C diets consisted of 16% alfalfa silage, 29% barley silage, 10% alfalfa hay, and 45% concentrate (Table 1, DM basis). The diets were formulated using the Cornell-Penn-Miner System (CPMDairy, Version 1.0) to supply adequate metabolizable energy and protein for a 600-kg cow producing 30 kg/d of milk with 3.5% fat and 3.2% CP.

The eNDF factor (**eNDFf**) for individual forages and ingredients was estimated using the Cornell-Penn-Miner Dairy system (version 1.0; $\mathbf{eNDFf}_{CPM}$) or using the Cornell Net Carbohydrate and Protein System (version 4.0; $\mathbf{eNDFf}_{CNCPS}$), and the eNDF factor of TMR was subsequently calculated. Particle length of the forages and TMR were measured using the PSPS and by dry sieving (Tables 2 and 3). The pef for forages and TMR were obtained in different ways: $\mathbf{pef}_{PS}$ was calculated as the sum of the DM proportions retained on the two sieves of the PSPS, and $\mathbf{pef}_{M}$ was calculated based on tabular values of Mertens (2000). The $\mathbf{pef}_{P>1.18}$ was determined as a percentage of DM remaining on 1.18-mm screen using a dry sieving technique. The peNDF was calculated by multiplying NDF content of the forage or TMR by pef determined for each system. Likewise, eNDF was calculated by multiplying NDF content of the forage or TMR by $\mathbf{eNDFf}_{CNCPS}$ or $\mathbf{eNDFf}_{CPM}$ for eNDF based on the Cornell Net Carbohydrate and Protein System ($eNDF_{CNCPS}$) or the Cornell-Penn-Miner System ($eNDF_{CPM}$), respectively.

Particle size distributions of feeds and TMR were measured by dry sieving using a vertical oscillating sieve shaker (Analysette 3; Fritsch, Oberstein, Germany) equipped with a stack of sieves (W. S. Tyler, Inc., Mentor, OH) arranged in descending mesh size. Sieve mesh sizes were 9.5, 6.7, 3.35, 1.18, 0.6 and 0.15 mm. Approximately 15 g of feed was placed on the top screen, and the stack of sieves was shaken until the distribution of material did not change (approximately 10 min). Based on the overbalancing principle described by Vaage et al. (1984), it was assumed that the minimum particle length of material retained on each sieve was equal to twice the diagonal dimension of the sieve aperture. The cumulative percentage of sample weight that was below this minimum size was calculated for each sieve size as detailed by Lammers et al. (1996). Mean particle length (**MPL**) was calculated as the particle length for which 50% of the cumulative percentage weight of the sample was retained (Vaage and Shelford, 1984).

Barley grain obtained from one source was used throughout the experiment. The barley was steam-rolled to a coarse or fine thickness. Degree of processing was quantified using a processing index (**PI**) as described by Yang et al. (2000) measured as the volume weight of the barley after processing, expressed as a percentage of its volume weight before processing. Ker-

nel thickness and width were measured with a micrometer caliper on 20 kernels for each processed barley.

Feed offered and orts were measured and recorded daily during the last 10-d of the period to calculate feed intake. Feed samples were collected once weekly, and orts were collected twice weekly for DM determination. Samples were ground through a 1-mm diameter screen (standard model 4, Arthur Thomas Co., Philadelphia, PA) and composited by period for analysis of OM, NDF, ADF, starch, and CP. Milk production was recorded daily, a.m. and p.m., during the last 10 d of the period and sampled on 5 consecutive days (a.m. and p.m.) in the last week of the period. Milk samples were preserved with potassium dichromate, stored at 4°C, and sent to the Central Alberta Milk Testing Laboratory (Edmonton, AB, Canada) for milk fat, CP, and lactose determination by using an infrared analyzer (Milk-O-Scan 605, Foss Electric, Hillerød, Denmark).

In Situ Measurements

The ruminal digestive kinetics of processed barley grain, alfalfa silage, barley silage, and alfalfa hay were determined in sacco. The methodology used for ruminal incubation and calculation of DM disappearance kinetics were similar to that previously described (Yang et al., 2000). Effective ruminal degradability (**ERD**) of DM was calculated by the equation

$$a + b \times c/(c + k)$$

where k = fractional passage rate (assumed to be 4%/h which was the average measured in the present study).

Ruminal pH, VFA and Ammonia

Ruminal pH was measured by placing an industrial electrode (model PHCN-37; Omega Engineering, Stanford, CT) into the ventral sac of the rumen within each cow for a 72-h period. The pH was measured every 15 s, and the data were averaged over a 15-min interval and recorded. Mean ruminal pH for each cow in each period was determined by averaging the data over the 72-h period. Hours during which pH was above 6.2 or below 5.8 were calculated assuming that change of pH

Table 2. Distribution of particles, particle length, and physical effectiveness factors of forages.

	Alfalfa silage		Barley silage		Alfalfa hay		
	Original	Rechopped	Original	Rechopped	Original	Rechopped	SE
Penn State Particle Separator sieving DM retention on sieve, %							
Top, 19 mm	3.9[a]	0.3[b]	5.6[a]	0.4[b]	20.6[a]	0.0[b]	1.3
Middle, 8-mm	65.1[a]	54.6[b]	57.4	61.4	26.1[a]	0.3[b]	2.5
Bottom	31.0[b]	45.2[a]	37.0	38.3	53.3[b]	99.7[a]	2.7
pef_{PS},[1] %	69.0[a]	54.8[b]	63.0	61.7	46.7[a]	0.3[b]	2.7
pef_{M},[2] %	85	70	85	80	85	70	. . .
$pef_{P>1.8}$,[3] %	84.0	83.3	89.5	86.9	65.1[a]	22.9[b]	3.7
$eNDFf_{CNCPS}$,[4] %	83	70	65	60	92	35	. . .
$eNDFf_{CPM}$,[5] %	83	75	93	90	75	60	. . .
Dry sieving DM retained on sieve, %							
9.5 mm	4.8	0.2	3.2	0.5	6.9[a]	0.0[b]	2.0
6.7 mm	6.4[a]	0.5[b]	1.4	1.5	3.7[a]	0.0[b]	0.7
3.35 mm	30.3[c]	22.4[d]	34.5	33.1	11.4[a]	0.1[b]	3.2
1.18 mm	42.5[b]	60.2[a]	50.4	51.7	43.2[a]	22.8[b]	1.2
0.6 mm	5.1	6.0	5.6	6.2	17.1[b]	29.7[a]	1.1
0.15 mm	9.5	9.2	4.3	5.2	14.6[b]	38.3[a]	2.3
<0.15 mm	1.4	1.6	0.6[d]	1.8[c]	3.2[b]	9.1[a]	0.4
MPL,[6] mm	8.2[c]	6.3[d]	8.2	7.6	5.2[a]	1.8[b]	0.7

[a,b]Means in the same row within same forage with different superscripts differ ($P < 0.05$).

[c,d]Means in the same row within same forage with different superscripts differ ($P < 0.15$).

[1]Physical effectiveness factor determined as the proportion of DM retained by both sieves of the Penn State Particle Separator.

[2]Physical effectiveness factor based on chewing determined from Mertens (2000).

[3]Physical effectiveness factor determined as a percent of DM remaining on a 1.18-mm screen measured using a dry sieving technique.

[4]Effective NDF factor determined from the Cornell Net Carbohydrate and Protein System (CNCPS, version 4.0).

[5]Effective NDF factor determined from the Cornell-Penn-Miner Dairy Model (CPMDairy, version 1.0).

[6]Fifty percent of the particles are greater or less than this length.

Table 3. Distribution of particles, particle length, and physical effectiveness factors of TMR.

	Grain processing		Fiber content		Forage particle length		
Item	Coarse	Flat	Low	High	Long	Short	SE
Penn State Particle Separator sieving							
DM retained on sieve, %							
Top, 19 mm	2.5	2.3	1.5[b]	3.3[a]	4.5[a]	0.3[b]	0.4
Middle, 8 mm	35.1[a]	31.7[b]	27.6[b]	39.2[a]	34.6[a]	32.2[b]	0.8
Bottom	62.3[b]	66.0[a]	70.8[a]	57.5[b]	60.9[b]	67.5[a]	0.8
pef_{PS},[1] %	37.7[a]	34.0[b]	29.2[b]	42.5[a]	39.1[a]	32.5[b]	0.7
pef_{M},[2] %	76.3[a]	73.0[b]	73.0[b]	76.3[a]	77.7[a]	71.6[b]	0.7
$pef_{P>1.18}$,[3] %	76.2	77.5	77.7	76.0	80.6[a]	73.1[b]	0.8
$eNDFf_{CNCPS}$,[4] %	55.5	55.5	51.8[b]	59.1[a]	61.2[a]	49.7[b]	0.1
$eNDFf_{CPM}$,[5] %	66.7	66.7	61.2[b]	72.1[a]	68.7[a]	64.7[b]	0.1
Dry sieving							
DM retained on sieve, %							
9.5 mm	1.1	1.7	1.6	1.2	2.6[c]	0.2[d]	1.0
6.7 mm	0.7	1.5	1.1	0.8	1.3[c]	0.6[d]	0.3
3.35 mm	28.6[c]	24.7[d]	31.1[a]	22.2[b]	30.2[a]	23.1[b]	1.3
1.18 mm	45.8[d]	50.0[c]	43.9[b]	51.9[a]	46.5	49.3	1.7
0.6 mm	9.6	9.2	8.3[b]	10.5[a]	8.0[b]	10.8[a]	0.7
0.15 mm	12.3	12.5	12.0	12.8	10.9[c]	13.9[d]	1.3
<0.15 mm	1.9[a]	0.9[b]	1.9[a]	0.9[b]	0.7[b]	2.1[a]	0.3
MPL,[6] mm	6.3	6.3	6.8[a]	5.9[b]	7.0[a]	5.6[b]	0.3

[a,b]Treatment means within a main effect differ ($P < 0.05$).

[c,d]Treatment means within a main effect tend to differ ($P < 0.15$).

[1]Physical effectiveness factor determined as the proportion of DM retained by both sieves of the Penn State Particle Separator.

[2]Physical effectiveness factor based on chewing determined from Mertens (2000). The pef of coarsely rolled barley was assumed to be 70%, and the pef of flatly rolled barley was assumed to be 60%.

[3]Physical effectiveness factor determined as a percent of DM remaining on a 1.18-mm screen measured using a dry sieving technique.

[4]Effective NDF factor determined from the Cornell Net Carbohydrate and Protein System (CNCPS, version 4.0).

[5]Effective NDF factor determined from the Cornell-Penn-Miner Dairy Model (CPMDairy, version 1.0).

[6]Fifty percent of the particles are greater or less than this length.

between two measuring times was linear. The lowest pH for each cow over the entire period was recorded. Ruminal fluid was collected on 1 d at 0900, 1200, and 1600 h from multiple sites in the rumen. Samples were immediately squeezed through four layers of cheesecloth with a mesh size of 250 μm. Five milliliters of filtrate was preserved by adding 1 ml of 25% HPO_3 to determine VFA, and 9 ml of filtrate was preserved by adding 1 ml of 1% H_2SO_4 to determine ammonia N. The samples were subsequently stored frozen at –20°C until analyses.

Duodenal Flow and Apparent Digestion

Duodenal flow and apparent digestion of nutrients in the total tract were determined using $YbCl_3$ (Rhône-Poulenc Inc., Shelton, CT). Marker solution was continuously infused into the rumen via ruminal cannulas with an automatic pump during the last 2 wk of the period. Daily amounts infused were 2.6 g of Yb dissolved in 850 ml of water for each cow. Ruminal, duodenal, and fecal samples were collected four 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 ruminal, duodenal, and fecal contents taken at 2-h intervals.

Duodenal samples were pooled by cow for each period using a blender/mixer (model MX-9100, Toshiba, Tokyo, Japan) and freeze-dried for chemical analysis. For fecal samples, the sample from each sampling time was mixed and divided into two subsamples (about 100 g for each). One was pooled by cow for each period, then dried at 55°C and ground through a 1-mm screen (standard model 4) for chemical analyses. The other subsample was immediately measured for pH using a pH meter by preparing of slurry of feces with distilled water.

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 content determined by combustion at 550°C overnight. Content of CP in the samples was determined by flash combustion (Carlo Erba Instruments, Milan, Italy). The methods described by Van Soest et al. (1991) were used in analyses of NDF and ADF with amylase and sodium sulfite used in the NDF procedure. Starch was determined by enzymatic hydrolysis of α-linked glucose polymers as described previously (Beauchemin and Rode, 1997). Ruminal VFA were separated and quantified by gas chromatography (Varian 3700; Varian Specialties Ltd., Brockville, ON) with a 15-m (0.53-mm i.d.) fused silica column (DB-FFAP column; J and W Scientific, Folsom, CA). Ammonia content of ruminal samples was determined using the method described by Weatherburn (1967) modified to use a microtiter plate reader. Contents of Cr, Yb, and Co in the samples were determined by atomic absorption spectrophotometry according to the AOAC (1990).

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.

Data were analyzed using the general linear models procedure of SAS (1989) to account for effects of square, period in square, cow in square, grain processing, F:C, forage particle length, and the two-way interactions between dietary factors. Effects were declared significant at $P < 0.05$ unless otherwise noted, and trends were discussed at $P < 0.15$. As there were very few significant interactions between dietary factors, only the main effects are presented in the tables; significant interactions are discussed in the text.

RESULTS

Forage and TMR Particle Length

For both silages, the proportion retained on the top screen of the PSPS was low (< 6%) even before rechopping (Table 2). In comparison, almost 21% of the chopped alfalfa hay was retained on the top sieve. Despite the greater proportion of long particles in alfalfa hay compared with the two silages, the pef_{PS} for alfalfa hay was much lower than for the silages because less hay was retained on the bottom sieve. The pef of feeds was significantly lower when measured directly as particle size with the PSPS (pef_{PS}) than when estimated from tables based on chewing time (pef_M) or particle size retained on the 1.18-mm screen ($pef_{P>1.18}$). The $eNDFf_{CNCPS}$ or $eNDFf_{CPM}$ were close to pef_M or $pef_{P>1.18}$, but also greater than pef_{PS}.

Rechopping the silages reduced pef_{PS}, but the reduction was less than expected, particularly in the case of barley silage. Rechopping reduced the proportion of long particles, but most of these accumulated on the bottom sieve, as the proportion of fine particles retained by the pan was not affected by rechopping. This is also confirmed by analysis of particle distribution measured by dry sieving. Rechopping silages reduced the proportion of coarse particles but did not change proportion of particles passing through the 1.18-mm screen, and, consequently, proportion of particles retained by the 1.18-mm screen was similar between original and rechopped silages. Rechopping the alfalfa hay dramatically reduced pef_{PS} and distribution of particles.

Analysis of the TMR indicated that increasing the extent of grain processing only reduced the pef_{PS} by 3.7 percentage units (10%) (Table 3). Reducing the particle length of the forage reduced the pef_{PS} of the TMR by 6.6 percentage units (17%) and reducing the forage content of the diet decreased the pef_{PS} by 13.3 percentage units (31%). As observed for forages, the pef_M of TMR estimated based on tabular values of Mertens (2000) or $pef_{P>1.18}$ estimated from particles retained on the 1.18-mm screen were also higher than the pef_{PS}. In addition, the pef_M and $pef_{P>1.18}$ of TMR were higher than the $eNDFf_{CPM}$ or the $eNDFf_{CNCPS}$ for TMR because the CPMDairy and CNCPS have lower eNDFf for barley grain than the model of Mertens (2000) and the $pef_{P>1.18}$ measured directly from particles retained on 1.18-mm screen, on which most of steam-rolled barley grain was retained.

In Situ Ruminal Digestion Kinetics

Increasing the extent of grain processing tended to increase the soluble fraction ($P < 0.12$), but substantially increased the rate of digestion of the slowly degradable fraction (Table 4). Consequently, ERD was increased by about 18 percentage units by more extensive processing of barley.

For forages, ERD was similar for alfalfa silage and barley silage, but both were about 9 percentage units lower in ERD compared with alfalfa hay (Table 4). Rate of digestion was highest for alfalfa hay, followed by alfalfa silage, and then barley silage. The soluble fraction was higher for alfalfa hay than for the other two forages, whereas the slowly degradable fraction was highest for barley silage, followed by alfalfa hay, and then alfalfa silage.

Table 4. In situ ruminal DM degradation of processed barley grain or forage.

Feed	Parameters[1] a, %	b, %	c, %/h	ERD, %
Barley grain[2]				
Coarse	3.6	87.1	2.71	30.6
Flat	5.8	71.3	9.20	48.9
SE	0.6	7.3	0.37	1.8
$P <$	0.12	0.27	0.01	0.02
Forage				
Alfalfa silage	24.8^{b}	32.0^{c}	5.81^{a}	40.4^{b}
Barley silage	24.3^{b}	50.2^{a}	2.99^{b}	40.5^{b}
Alfalfa hay	28.2^{a}	37.8^{b}	8.11^{a}	49.6^{a}
SE	1.1	1.8	0.81	1.9
$P <$	0.08	0.01	0.01	0.01

[1]Parameters were calculated from the fitted equation $P = a + b(1 - e^{-c(t-L)})$ for $t > L$, where P = percentage of DM disappearance from the nylon bag at time t, a = soluble fraction, b = slowly degradable fraction, c = fraction rate constant at which b is degraded, L = lag time (hours), and t = time of incubation (hours). Effective ruminal degradability (ERD) was calculated using equation $a + bc/(c + k)$, where k = 4%/h.

[2]Processing index was 76 and 60% for coarsely and flatly rolled barley, respectively.

Intakes

Dry matter intake, and consequently OM, starch, NDF, and ADF intakes, were increased with flatly rolled barley compared with coarsely rolled barley (Table 5). Increasing the F:C had no effect on DMI, although intake of OM ($P < 0.08$) tended to be reduced, and as expected, intakes of NDF and ADF increased. Reducing the particle size of the forage had no effect on intake.

Intake of peNDF was greater when the F:C or forage particle length was increased regardless of the model used for the estimation of peNDF (Table 5). However, reducing the extent of grain processing only increased peNDF when estimated with the PSPS or the model of Mertens (2000). The other systems consider the pef to be identical for coarsely or flatly rolled barley.

Ruminal and Total Tract Digestibilities

Increasing the extent of grain processing increased the apparent total tract digestibility of DM, OM, and starch (Table 6). The 10% (from 81.7 to 90.2%) increase in total tract digestibility of starch was due to a 33% improvement in ruminal digestion (from 37.8 to 50.1%) and a 15% improvement in postruminal digestion (from 68.4 to 78.7%).

Increasing the proportion of forage in the TMR decreased apparent digestibility of DM and OM in the total tract (Table 6). Digestion of starch in the rumen tended to decrease ($P < 0.09$), but postruminal digestion of starch increased ($P < 0.02$) with a high F:C in the diet. Consequently, a greater proportion of the starch consumed was digested postruminally with high F:C in the diet. Despite increased postruminal digestion of starch, fecal pH was higher with higher fiber diets.

Forage particle length had no effect on digestibility of DM, OM or starch in the total tract or in the rumen

Table 5. Intake of dairy cows as affected by grain processing, dietary fiber content, or forage particle length.

Intake	Grain processing Coarse	Flat	Fiber content Low	High	Forage particle length Long	Short	SE
DM							
kg/d	19.5^{b}	20.7^{a}	20.5	19.8	20.3	19.9	0.4
% of BW	3.09^{b}	3.27^{a}	3.24^{c}	3.12^{d}	3.20	3.16	0.05
OM, kg/d	17.6^{b}	18.8^{a}	18.7^{c}	17.7^{d}	18.3	18.1	0.4
Starch, kg/d	5.49^{b}	6.08^{a}	6.80^{a}	4.77^{b}	5.73	5.83	0.15
NDF, kg/d	6.87^{b}	7.29^{a}	6.69^{b}	7.47^{a}	7.10	7.06	0.13
Effective NDF, % of DMI							
$peNDF_{PS}$,[1] %	11.5^{a}	10.3^{b}	8.3^{b}	13.5^{a}	12.3^{a}	9.5^{b}	0.16
$peNDF_{M}$,[2] %	23.0^{a}	21.9^{b}	20.8^{b}	24.2^{a}	24.2^{a}	20.8^{b}	0.23
$peNDF_{P>1.18}$,[3] %	23.0	23.2	22.2^{b}	24.1^{a}	25.0^{a}	21.2^{b}	0.27
$eNDF_{CNCPS}$,[4] %	16.8	16.7	14.8^{b}	18.8^{a}	19.1^{a}	14.5^{b}	0.19
$eNDF_{CPM}$,[5] %	20.2	20.1	17.4^{b}	22.8^{a}	21.4^{a}	18.8^{b}	0.22
ADF, kg/d	4.11^{b}	4.37^{a}	3.63^{b}	4.84^{a}	4.23	4.24	0.08

[a,b]Treatment means within a main effect differ ($P < 0.05$).

[c,d]Treatment means within a main effect tend to differ ($P < 0.15$).

[1]Physically effective NDF measured as the NDF content of the TMR multiplied by pef_{PS} (Table 3).

[2]Physically effective NDF measured as the NDF content of the TMR multiplied by pef_{M} (Table 3).

[3]Physically effective NDF measured as the NDF content of the TMR multiplied by $pef_{P>1.18}$ (Table 3).

[4]Effective NDF measured as the NDF content of the TMR multiplied by $eNDFf_{CNCPS}$ (Table 3).

[5]Effective NDF measured as the NDF content of the TMR multiplied by $eNDFf_{CPM}$ (Table 3).

Table 6. Digestibility of OM and starch and fecal pH in dairy cows as affected by grain processing, dietary fiber content, or forage particle length.

	Grain processing		Fiber content		Forage particle length		
Item	Coarse	Flat	Low	High	Long	Short	SE
DM							
ADTT,[1] %	58.6[b]	63.6[a]	63.2[a]	59.1[b]	61.8	60.4	0.8
OM							
RFOM,[2] kg/d	8.5	9.2	9.0	8.8	8.5	9.2	0.5
Flow to duodenum, kg/d	12.4	12.9	12.8	12.5	13.1[c]	12.2[d]	0.4
Digestibility							
Ruminal (truly), %	48.2	49.1	47.7	49.5	46.4	50.9	2.4
Postruminal							
% of OM intake	30.7	34.2	33.7	31.2	35.3[c]	29.6[d]	2.3
% of flow to duodenum	42.2[b]	49.0[a]	47.9[c]	43.2[d]	48.3[a]	42.8[b]	1.6
ADTT, %	60.1[b]	65.3[a]	64.7[a]	60.7[b]	63.4	62.0	0.8
Starch							
Flow to duodenum, kg/d	2.35	2.99	3.47	2.86	3.26	3.08	0.17
Digestibility							
Ruminal, %	37.8[b]	50.1[a]	48.3[c]	39.6[d]	41.2	46.7	3.3
Postruminal							
% of starch intake	43.9	40.1	37.0[b]	47.0[a]	45.7[c]	38.3[d]	2.8
% of flow to duodenum	68.4[b]	78.7[a]	71.2[b]	75.8[a]	76.4[a]	70.6[b]	1.2
ADTT,[3] %	81.7[b]	90.2[a]	85.3	86.6	86.9	85.0	0.9
Fecal pH	6.95	6.89	6.73[b]	7.11[a]	6.87	6.96	0.08

[a,b]Treatment means within a main effect differ ($P < 0.05$).

[c,d]Treatment means within a main effect tend to differ ($P < 0.15$).

[1]Apparently digested in the total tract.

[2]Organic matter truly fermented in the rumen.

[3]Interaction between grain processing and F:C ratio significant ($P = 0.02$).

(Table 6), although digestibility of OM or starch in the intestine was lower with reduced forage particle length.

Ruminal and postruminal digestibility of NDF was not affected by grain processing, F:C, or forage particle length (Table 7). However, total tract digestibility of NDF was lowered by increasing the F:C, mostly attributed to a numerical decrease in postruminal digestion of NDF. Similarly, ruminal digestibility of ADF was not affected by grain processing or forage particle length. However, ruminal ADF digestibility increased, while postruminal digestion decreased by increasing the F:C in the diet. Consequently, digestion of ADF in the total tract was higher for the high forage diet. Thus, there was an apparent contradiction for the digestibility results obtained for NDF and ADF in the total tract.

Rumen pH

The diurnal patterns of ruminal pH were generally similar among the treatments (Figure 1). The highest pH values were observed just before the afternoon feeding at 1500 h, while the lowest pH values were at night between 2100 and 0300 h. Cows fed flatly rolled barley had consistently lower ruminal pH than cows fed coarsely rolled barley, which resulted in a lower mean pH (Table 8). In addition, increasing the extent of grain processing decreased the duration each day that pH remained above 6.2 and almost doubled the duration that pH remained below 5.8.

Forage-to-concentrate ratio of the diets had no effect on any of the pH variables measured. In addition, reducing forage particle size had no effect on mean pH, but duration that pH remained above 6.2 each day tended to be lower for the cows fed short particle forage ($P < 0.10$).

The lower ruminal pH with flatly rolled barley did not correspond to higher total ruminal VFA concentration. However, as expected, cows fed high forage diets had relatively higher acetate and lower propionate proportions, which resulted in a higher acetate-to-propionate ratio. Impact of the treatments on the concentration of ammonia N in ruminal fluid was minimal.

Production and Composition of Milk

Milk production (actual) was increased by 1.1 kg/d, while 4% FCM was increased ($P < 0.07$) only by 0.6 kg/d, when coarsely rolled barley was replaced by flatly rolled barley in the diets of cows (Table 9). More extensive processing of grain reduced fat content ($P < 0.06$), but increased CP content of milk which resulted in more yield of milk CP.

Increasing F:C decreased milk production, but production of 4% FCM was not affected by forage level, because milk fat content was inversely related to milk production. Increasing yield of milk CP with low F:C was due to combined effects of increasing milk yield and milk protein content.

Reducing the particle size of forage had no effect of milk production, but tended to reduce ($P < 0.12$) milk fat and milk protein contents, such that production of 4% FCM tended to be lower ($P < 0.15$) for cows fed short than for cows fed long forage particles.

DISCUSSION

Grain Processing

Increasing the extent of grain processing increased milk yield of cows by about 1 kg/d, confirming our previous findings (Yang et al., 2000). Increased milk production due to more extensive grain processing was due to an increase in DMI and total tract digestibility of nutrients. Reasons for lower DMI by cows fed coarsely rolled barley are not fully understood, although this observation is in agreement with our previous study (Yang et al., 2000). In that study, lower DMI of cows fed coarsely rolled barley could be attributed to lower ruminal OM digestion and slower passage of particulate matter from the rumen. In the present study, ruminal digestion of OM and rate of passage of forage from the rumen (data not presented) were not significantly affected by grain processing.

Increasing the degree of barley processing improved the digestibility of DM and OM in the total tract, due mainly to increased starch digestibility as there were no effects of grain processing on fiber digestibility. Both ruminal and postruminal digestion of starch were improved by reducing PI of barley. Increased processing of barley grain was beneficial because it removed the physical barriers to microbial digestion of the kernels in the rumen, and increased surface area of feed particles which helped increase postruminal digestion and absorption. Increasing the extent of barley processing favors both ruminal and intestinal digestion of starch (Yang et al., 2000).

In contrast to starch, there were no effects of grain processing on ruminal or total tract digestion of fiber. This is somewhat surprising because increased ruminal fermentation of starch due to grain processing decreased ruminal pH. Mean ruminal pH differed between cows fed diets containing coarsely or flatly rolled barley by 0.13 units, and time that pH remained below 5.8, the threshold for subclinical ruminal acidosis, almost doubled for cattle fed finely rolled barley. However, combining the results for all animals and periods for each diet (n = 16) or over both diets (n = 32) showed no relationship between rumen pH and ruminal fiber digestion (Table 10). Mean pH ranged from 5.58 to 6.55 and time that pH < 5.8 ranged from 0 to 15.7 h/d. Thus, a wide range in pH conditions were obtained. Fiber digestion in the rumen was also variable, ranging from 25.8 to 63.4%. However, correlation coefficients be-

Table 7. Digestibility of NDF and ADF of dairy cows as affected by grain processing, dietary fiber content, or forage particle length.

	Grain processing		Fiber content		Forage particle length		
Item	Coarse	Flat	Low	High	Long	Short	SE
NDF							
Flow to duodenum, kg/d	4.15[d]	4.52[c]	4.09[b]	4.57[a]	4.42	4.25	0.12
Digestibility							
Ruminal, %	39.3	37.8	38.7	38.5	39.7	37.5	1.8
Postruminal							
% of NDF intake	6.5	8.7	9.2	6.0	9.3	5.9	1.6
% of NDF flow to duodenum	8.3	12.3	13.3	7.3	13.0	7.5	2.8
ADTT,[1] %	45.8	46.5	47.9[a]	44.5[b]	46.7	45.6	0.7
ADF							
Flow to duodenum, kg/d	2.80[d]	3.10[c]	2.71[b]	3.20[a]	3.01	2.89	0.10
Digestibility							
Ruminal, %	31.3	28.4	25.7[b]	34.0[a]	31.3	28.4	2.2
Postruminal							
% of ADF intake	5.8[b]	11.3[a]	11.3[a]	5.8[b]	10.5[c]	6.5[d]	1.7
% of ADF flow to duodenum	6.3[d]	14.4[c]	13.3	7.4	13.3	7.3	2.9
ADTT,[1] %	37.1	39.6	37.0[c]	39.7[d]	38.9	37.8	1.2

[a,b]Treatment means within a main effect differ ($P < 0.05$).

[c,d]Treatment means within a main effect tend to differ ($P < 0.15$).

[1]Apparently digested in the total tract.

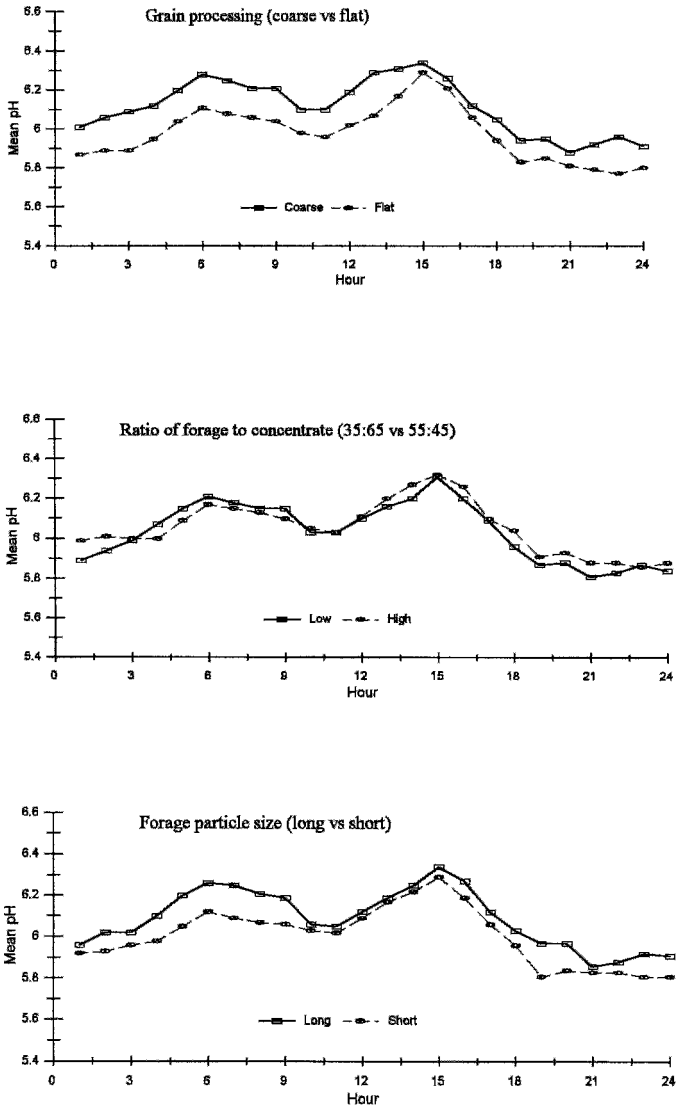

Figure 1. Diurnal fluctuation of rumen pH affected by grain processing, ratio of forage to concentrate, or forage particle size in lactating dairy cows.

tween ruminal pH and ruminal NDF digestion were low (r = 0.21 with pH measured as mean pH, $P > 0.15$; r = 0.29 with area under pH curve, $P < 0.15$; and r = 0.09 with pH measured as hours pH < 5.8, $P > 0.15$).

Based on the results of the present study, it is clear that extensive rolling of barley maximizes ruminal and postruminal digestibility of starch. Although digestibility increased, increased fermentation rate reduced ruminal pH and increased the incidence of subclinical acidosis. Furthermore, the increased incidence of subclinical acidosis and decreased fat content of milk could not have been predicted from the intake of peNDF or eNDF. There was no correlation between ruminal pH and intake of peNDF or eNDF, regardless of how it was estimated (Table 10). It must be cautioned that the duration of feeding for each diet in this study was relatively short term, and the effects of these diets over an entire lactation are not known.

F:C Ratio

Increased F:C in the diet of cows decreased milk production, confirming results of other studies (Beauchemin et al., 1994b; Beauchemin and Rode, 1997). This decrease in milk production was related to lower energy content of the diet, lower DMI, and lower digestion of OM in the total tract. Despite lower milk production, milk fat content tended to be higher ($P < 0.12$), so production of FCM was not affected by the proportion of forage in the diet. The lack of effect of F:C on FCM production is consistent with some reports (Beauchemin and Buchanan-Smith, 1989; Beauchemin et al., 1994b) but opposite to others (Beauchemin and Rode, 1997). In a previous study with barley-based diets, we observed that FCM was maximized when diets were formulated to supply 19.5 to 25% NDF from forage but was reduced when NDF was increased further because of a decline in energy intake (Beauchemin and Rode, 1997). The results from the present study would suggest that as low as 15% NDF from forage can be fed without decreasing FCM, although milk fat content will likely be reduced.

The variation in intakes of OM, starch, NDF, and ADF with changes in F:C reflected the composition of the diet consumed because DMI was not affected by F:C. Similar ruminal digestibility of OM between low and high F:C resulted from the balance of higher ruminal digestion of starch, but lower ruminal digestion of ADF, for diets containing low versus high F:C. Higher digestibility of DM or OM in the total tract with low F:C agreed with others (Rode et al., 1985; Sarwar et al., 1992).

The effects of F:C on ADF and NDF digestion were inconsistent, and the causes of this are unclear. Probably because as F:C increased, the alfalfa made up a bigger proportion of the ADF and NDF; if alfalfa NDF digestion were lower than barley NDF or barley ADF digestion in the total digestive tract were lower than alfalfa ADF, this would explain the differences in the total tract digestion of ADF and NDF. Ruminal pH was surprisingly unaffected by F:C, which is consistent with the lack of dietary effect on ruminal NDF digestion. Furthermore, no relationship existed between the intake of NDF and rumen pH (Table 10, r = –0.06; $P > 0.15$) when combining the results for all animals and periods over both diets (n = 32). Thus, although diets differed substantially in pef_{PS}, and intake of $peNDF_{PS}$ varied by 62.7%, there was no effect on rumen pH.

Table 8. Characteristics of ruminal fermentation in dairy cows as affected by grain processing, dietary fiber content, or forage particle length.

	Grain processing		Fiber content		Forage particle length		
Item	Coarse	Flat	Low	High	Long	Short	SE
pH							
Average	6.11[c]	5.98[d]	6.04	6.06	6.09	5.99	0.05
Area under curve	143.0[c]	140.5[d]	141.7	141.8	143.0[c]	140.6[d]	1.0
(pH × h/d)							
>6.20, h	9.8	7.6	9.1	8.3	10.2[c]	7.2[d]	1.2
<5.80, h	4.1[b]	7.9[a]	5.9	6.1	5.0	7.0	1.0
Lowest	5.57[a]	5.36[b]	5.43	5.50	5.47	5.46	0.06
VFA							
Total, m*M*	112.3	116.0	114.0	114.3	117.6[c]	110.8[d]	3.1
mol/100 mol							
Acetate (A)	64.0	63.3	61.8[b]	65.5[a]	63.5	63.8	0.6
Propionate (P)	19.4	20.3	21.3[a]	18.4[b]	20.1	19.7	0.8
Butyrate	11.8	12.0	12.3	11.5	11.8	12.1	0.5
A:P	3.36	3.24	2.99[b]	3.62[a]	3.26	3.34	0.13
NH_3 N, mM/L	3.29[c]	3.15[d]	3.33[a]	3.11[b]	3.28	3.16	0.06

[a,b]Treatment means within a main effect differ ($P < 0.05$).

[c,d]Treatment means within a main effect tend to differ ($P < 0.15$).

Furthermore, intake of $peNDF_{PS}$ was less than recommended (Lammers et al., 1996; Mertens, 2000).

Forage Particle Length

The original alfalfa and barley silages used in this study were of average particle length with pef_{PS} typical to those fed in many commercial dairy operations. Despite the average pef_{PS} of the original silages used in the present study, the proportion retained on the top sieve tended to be fairly low compared with recommendations (Lammers et al., 1966). The rechopped alfalfa silage represented a fine silage; but rechopped barley silage was of average particle length.

In a survey of barley silage samples (n = 52) used in beef and dairy operations in Alberta, we observed a median pef_{PS} of 63% (unpublished data). Barley silages with a $pef_{PS} < 55\%$ were considered fine, $pef_{PS} = 55$ to 72% considered average, and $pef_{PS} > 72\%$ considered coarse. In those samples, the proportion retained on the top sieve of the PSPS varied from 4 to 42%, with a mean of 6.4%, 9.9%, and 16.8% for fine, average, and

Table 9. Milk production and composition of dairy cows as affected by grain processing, dietary fiber content, or forage particle length.

	Grain processing		Fiber content		Forage particle length		
Item	Coarse	Flat	Low	High	Long	Short	SE
Milk yield, kg/d							
Actual	23.1[b]	24.2[a]	24.2[a]	23.1[b]	23.7	23.6	0.3
4% FCM	22.6[d]	23.2[c]	23.1	22.7	23.1[c]	22.7[d]	0.2
Component yield, kg/d							
Fat	0.89	0.90	0.89	0.90	0.91[c]	0.88[d]	0.01
Protein	0.73[b]	0.79[a]	0.79[a]	0.73[b]	0.77	0.76	0.01
Lactose	1.05[b]	1.11[a]	1.11[a]	1.05[b]	1.08	1.08	0.01
Milk component, %							
Fat	3.94[d]	3.77[c]	3.79[d]	3.93[c]	3.92[c]	3.79[d]	0.06
Protein	3.26[b]	3.32[a]	3.33[a]	3.26[b]	3.31[c]	3.27[d]	0.02
Lactose	4.54	4.58	4.58	4.54	4.57	4.55	0.02
4% FCM/DMI	1.16	1.12	1.12	1.15	1.14	1.13	0.03
BW	634	635	633	636	637	632	3.4
BCS	2.60	2.58	2.59	2.58	2.60	2.58	0.02

[a,b]Treatment means within a main effect differ ($P < 0.05$).

[c,d]Treatment means within a main effect tend to differ ($P < 0.15$).

Table 10. Pearson correlation coefficients[1] for parameter measurements among 32 observations.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. DMI, kg/d														
2. NDF intake, kg/d	0.74													
3. Ruminal digestibility of NDF, %	0.26	0.22												
4. Ruminal digestibility of starch, %	0.20	–0.05	0.45											
5. Rumen pH	–0.16	–0.06	0.21	–0.27										
6. Area under curve (pH * h/d)	–0.15	–0.04	0.29	–0.26	0.96									
7. pH > 6.2, h/d	–0.18	–0.15	0.18	–0.29	0.91	0.90								
8. Milk fat content, %	0.08	0.05	0.00	–0.15	0.10	0.18	–0.06							
9. $peNDF_{PS}$, % of DMI	0.10	0.47	–0.03	–0.43	0.13	0.13	0.05	0.15						
10. $peNDF_{P>1.18}$, % of DMI	0.16	0.70	0.05	–0.34	0.04	0.10	0.04	0.09	0.78					
11. $peNDF_{M}$, % of DMI	0.03	0.62	0.08	–0.40	0.19	0.20	0.11	0.13	0.93	0.91				
12. $eNDF_{CPM}$, % of DMI	0.00	0.59	0.00	–0.35	0.12	0.11	0.01	0.11	0.96	0.80	0.93			
13. $eNDF_{CNPNS}$, % of DMI	0.03	0.58	0.01	–0.35	0.15	0.17	0.11	0.13	0.92	0.91	0.97	0.93		
14. DM retained on top sieve of PSPS	–0.03	0.32	0.03	–0.29	0.25	0.28	0.28	0.14	0.75	0.76	0.78	0.68	0.88	
15. DM retained on 2nd sieve of PSPS	–0.20	0.26	–0.09	–0.42	0.08	0.05	–0.02	0.13	0.92	0.51	0.75	0.86	0.73	0.56

[1]Correlation coefficients were significant at $P < 0.01$ (> 0.44 or < –0.44), $P < 0.05$ (> 0.35 or < –0.35), and $P < 0.15$ (> 0.27 or < –0.27).

coarse silages, respectively. For alfalfa silage, Heinrichs and Lammers (1997) reported an average pef_{PS} of 56.5%, and previously, we observed a pef_{PS} of 47% and 77%, respectively, for fine and coarse alfalfa silage (theoretical length of chop of 5 and 10 mm, respectively) (Beauchemin et al., 1994b). In that study (Beauchemin et al., 1994b), only 2.4% of the fine silage was retained on the top sieve of the PSPS, compared with 44.0% of the coarse silage. Heinrichs and Lammers (1997) reported for legume and legume silage mixtures (n = 2815), an average of 16% of the weight, and for small grain silages (n = 529), an average of 15% was retained on the top sieve.

Analysis of the TMR indicated that increasing the F:C of the diet, rather than increasing the particle length of forages or the processing of grain, had the largest effect on pef_{PS} for the TMR. Tabular estimates of pef_{M} based on chewing time were higher for forages compared with estimates of pef_{PS} based on sieving with PSPS, confirming a previous comparison (Mertens, 2000). Similarly, estimates of pef_{M} were greater than those of pef_{PS} for TMR because the PSPS method did not capture most of the grain on the sieves.

The pe of the diet is thought to influence chewing time, and consequently ruminal pH (Mertens, 1997). However, the present study showed no correlation between chewing time and rumen pH (data not shown), and no effect of forage particle length of the diet on rumen pH. Furthermore, when the data were combined for the entire study (n = 32), there was no relationship between intake of peNDF measured as the NDF content of the TMR multiplied by pef_{ps} (**$peNDF_{PS}$**), expressed either as kilograms per day or as a percentage of DMI, and rumen pH, measured either as mean pH or time pH < 5.8 (Figure 2). Similarly, there was no relationship between intake of peNDF measured as the NDF content of the TMR multiplied by pef_{ps} (**$peNDF_{M}$**), $eNDF_{CPM}$, or $eNDF_{CNCPS}$ and rumen pH (Table 10). Notably, there was a low correlation ($r = 0.28$; $P < 0.15$) between rumen pH, expressed either as area under the curve or time pH > 6.2, and DM retained by the top sieve of the PSPS (Table 10).

The lack of direct effect of peNDF on rumen pH is not surprising. It is well established that time spent chewing during eating and ruminating is correlated to intake of peNDF (Mertens, 1997), and that saliva secretion is about 1.5 to 2 times higher during chewing compared with during resting (Cassida and Stokes, 1986). However, the increase in total daily saliva output due to increased chewing is not as great as often assumed. This is because eating and ruminating time decreases resting time and the accompanying resting saliva secretion. Increased chewing time by 3.4 h/d (Beauchemin et al., 1994b) was estimated to only increase total daily saliva production by 4% (Beauchemin, 2000). It is likely that rumen pH and the extent of subclinical ruminal acidosis cannot be predicted directly using only the physical characteristics of the diet, as the rumen fermentability of starch appears to have larger effects on pH than the physical characteristics of feeds.

Interactions Between Dietary Factors

Previously it was concluded that barley should be extensively rolled to maximize its digestibility (Yang et al., 2000). However, diets in that study contained adequate levels of fiber, and extensively rolled barley did not produce severe digestive disturbances. The feed industry often adjusts the degree of processing of barley grain as a means of limiting ruminal availability of starch and preventing acidosis. The present study was designed to examine whether the effects of grain pro-

cessing depend upon intake of peNDF, varied either due to F:C of the diet or particle size of the forage.

A few interactions between grain processing and F:C were observed. The increase in apparent total tract digestibility of starch due to extensively rolling of barley was highest for diets containing low F:C diets that contained the highest concentration of starch. In high forage diets, apparent total tract digestibility of starch increased from 84.1 to 89.1%, while in low forage diets starch digestibility increased from 79.3 to 91.3%. Furthermore, an interaction ($P = 0.06$) between grain processing and F:C was observed for milk fat content. The decline in milk fat content due to grain processing was greatest for diets containing low F:C (from 3.89 to 3.69%), compared with diets containing high F:C (from 3.99 to 3.86%).

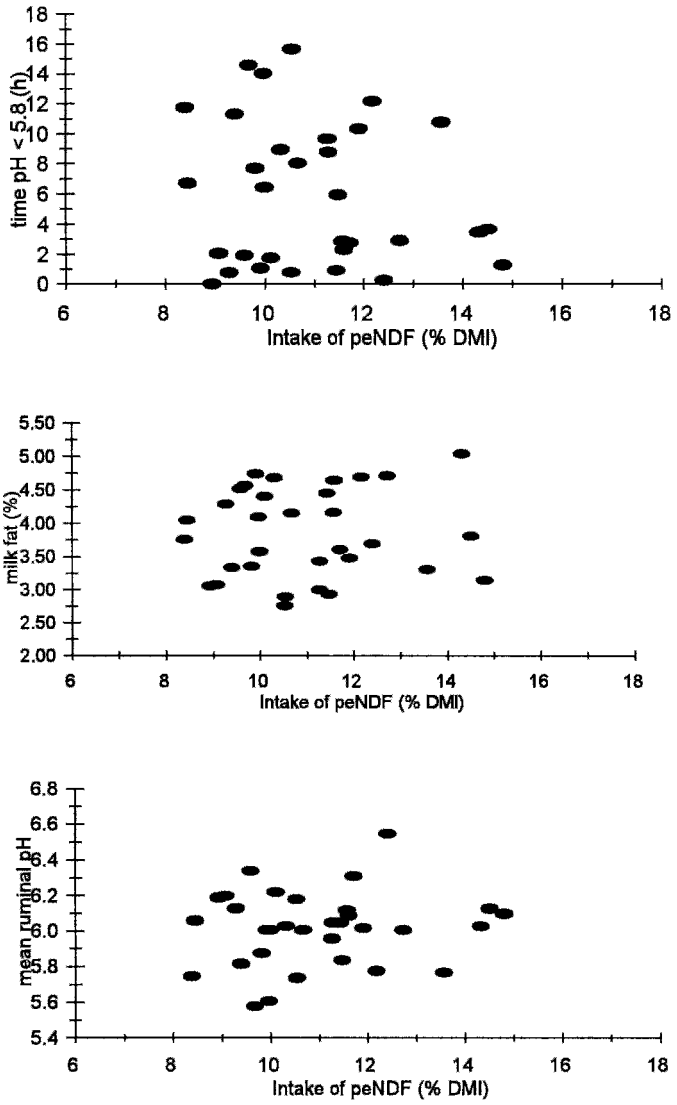

Figure 2. Relationship between intake of physically effective fiber measured using the Penn State Particle Separator and rumen pH, time ruminal pH remained below 5.8, and milk fat content ($r^2 = 0.02$, 0.02, and 0.003, respectively; $P > 0.05$).

Very few interactions between F:C and forage particle size were observed. The exception was for milk fat content for which an interaction ($P = 0.06$) between F:C and particle size was observed. The increase in milk fat content due to increased particle size was greatest for diets containing long particle forage. Increasing the particle length of the diet increased milk fat from 3.73 to 3.85% for diets containing low F:C, compared with an increase in milk fat from 3.84 to 4.00% for diets containing a high F:C. This is because increasing particle length of forages increases the intake of peNDF to a greater extent when forages comprise a larger portion of the diet. For example, in this study, intake of $peNDF_{PS}$ increased from 7.6 to 9.1% of DMI (+1.5% of DMI) for the low fiber diets, and from 11.4 to 15.6% of DMI (+4.2% of DMI) for the high fiber diets. A similar interaction was reported for coarse ($pef_{PS} = 77\%$) and fine ($pef_{PS} = 47\%$) alfalfa silage in diets containing less than adequate (12%) or adequate NDF from forage (22%) (Beauchemin et al., 1994a). Milk fat content increased when coarse silage replaced fine silage, but the increase was greatest with the higher fiber diet.

CONCLUSIONS

Increasing the ruminal availability of starch by more extensively rolling barley improved milk production due to increased DMI and digestibility. Both ruminal and postruminal digestion of starch were improved when the PI was reduced from 75.5 to 60.2%. However, increasing the rumen availability of starch reduced ruminal pH, an effect that was not predicted by intake of eNDF or pe fiber. Milk fat content also declined, but this was due to the supply of energy precursors rather than a direct effect of rumen pH on fiber digestion.

Increasing the intake of eNDF or peNDF by increasing the F:C or the particle size of forage had no effect on mean rumen pH or the incidence of subclinical ruminal acidosis in cows fed barley-based diets. This study indicates that the rumen fermentability of starch has a larger effect on rumen pH than the physical characteristics of feeds. Measuring eNDF or peNDF of the diet may not be a good indicator of the incidence of subclinical acidosis in dairy cows fed diets that are highly digestible in the rumen.

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