Minimum Versus Optimum Concentrations of Fiber in Dairy Cow Diets Based on Barley Silage and Concentrates of Barley or Corn[1]

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ABSTRACT

Six primiparous and 6 multiparous lactating Holstein cows were used in a double 6 × 6 Latin square to determine the effects of the percentage of forage fiber in diets containing concentrates based on barley or corn. Cows received one of six diets that provided three percentages of neutral detergent fiber (NDF) from barley silage [19.5, 25.0, and 40.9% of dry matter intake (DMI)] combined with concentrates based on either barley or corn.

The DMI (18.6 vs. 18.3 kg/d) and net energy for lactation (27.2 vs. 26.8 Mcal/d) were similar for cows fed barley and corn diets, respectively. Consequently, milk yield (25.7 vs. 25.0 kg/d) and fat-corrected milk yield (22.3 vs. 21.7 kg/d) were not affected by type of grain. Milk yields were similar for cows fed low and medium NDF diets, but yields declined when NDF from forage exceeded 25% of DMI because of declining intake of net energy for lactation. Effects of increased fiber from forage on milk fat content differed depending on diet; the low NDF diet based on barley caused milk fat to decline. Rumination time was higher for diets based on barley than for diets based on corn (516 vs. 469 min/d), and, as the percentage of forage fiber in the diet increased from low to high, rumination time increased more for cows fed diets based on corn than for cows fed diets based on barley.

The minimum amount of forage fiber necessary in diets to avoid milk fat depression appeared to be higher for barley diets than for corn diets, although milk fat depression may not be a valid criterion by which to assess minimum fiber concentrations. Further research is needed to determine the minimum concentration of forage fiber needed to ensure healthy ruminal function and cow longevity.

(**Key words**: barley, corn, neutral detergent fiber, chewing)

Abbreviation key: **NDFF** = NDF from forage sources.

INTRODUCTION

To meet the energy requirements of lactating dairy cows, the proportion of concentrate in the diet is commonly increased, and high quality forages containing relatively low amounts of fiber are used. However, for dairy cows, diets that are low in fiber are associated with ruminal acidosis; reduced rumination, saliva secretion, and fiber digestion; lower ratios of acetate to propionate; and milk fat depression (3). To maintain healthy ruminal function and to avoid milk fat depression, the NRC (21) recommends a minimum of 25 to 28% fiber, measured as NDF, with 75% of the total dietary NDF being supplied by forages. These recommendations are based on studies that mainly used concentrates based on corn. Mertens (20) suggested that formulating dairy cow diets to supply more than this minimum amount could maximize DMI and FCM. The optimal NDF concentration, however, depended on the milk yield potential of the cows; 4% FCM was maximal at 36% NDF for cows in late lactation that yielded about 20 kg/d, but 32% NDF optimized FCM yield for cows that yielded 30 kg/d in early lactation. Others have reported that FCM yield was negatively correlated with the concentration of NDF in diets consisting of corn grain and various sources of forages (5, 17, 23); the highest milk yield occurred at 24 to 26% NDF (5, 17). Briceno et al. (11) reviewed 20 experiments in which corn grain was used and reported a curvilinear decrease in FCM as dietary NDF increased.

Minimal and optimal concentrations of dietary NDF may depend on the source of cereal grain (29). The NDF content of barley (19 to 25%) is higher than that of corn (7%), making it impossible to meet the NRC (21) criteria for minimum fiber. Alternatively, it has been suggested that diets should be formulated

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to supply a minimum of 19 to 21% NDF from forage sources (**NDFF**) without consideration of the NDF from concentrates. In several studies that used concentrates based on barley (4, 6), lowering the NDF content of the diet increased milk yield, but milk fat content decreased. Therefore, FCM was unaffected by dietary NDF concentration, and no optimal concentration of NDF was determined. In addition, the concentration of NDFF that was necessary to prevent milk fat depression in diets based on barley seemed to be higher than that in diets based on corn (6, 29), presumably because of the more rapid and extensive ruminal fermentation of barley (18, 26). Beauchemin and Beauchemin et al. (4, 6) observed that for diets based on barley, between 25 and 28% NDFF was needed to maintain a milk fat content of 3.5%. Of course, for both barley and corn diets, the concentration of NDFF that was necessary to prevent milk fat depression also depended on other feeding practices, such as inclusion of high fiber by-product feeds, particle size of the forage, processing of the grain, frequency of feeding, and the use of total mixed rations (14).

Although there is some indication that more forage fiber may be needed to maintain high concentrations of milk fat when barley is fed rather than corn, surprisingly few studies have directly compared the response to fiber concentrations in barley versus corn diets. The objective of this study was to determine the effects of NDFF in diets that consisted of concentrates based on barley or corn on intake, chewing activities, digestion, and milk yield and composition.

MATERIALS AND METHODS

Cows and Diets

Twelve lactating Holstein cows were used in an experiment designed as a double 6 × 6 Latin square and balanced for residual effects of diets; rows (cows) and periods were the blocking factors. Primiparous cows were used in square 1 and averaged 48 DIM (SD = 16); multiparous cows fitted with ruminal cannulas were used in square 2 and averaged 56 DIM (SD = 12) at the start of the experiment. Cows in square 2 started the experiment about 1 mo later than did cows in square 1.

Cows received one of six diets during each 21-d experimental period. The diets were a factorial set; three concentrations of NDFF in the diet (low, medium, and high) were combined with concentrates based on either barley or corn. The target NDFF concentrations were 19, 25, and 40% (DM basis) for diets with low, medium, and high percentages of NDFF, respectively. Barley silage that was harvested in the mid-dough stage with a 0.95-cm theoretical chop length was the sole source of forage. All diets were formulated to meet or exceed NRC (21) requirements for CP, RUP, vitamins, and minerals. The composition of ingredients is given in Table 1, and diet formulations are provided in Table 2.

Cows were fed for ad libitum intake throughout the experiment. Concentrate was allocated in equal portions twice daily, and silage was available throughout the day. The DM (55°C) content of silage was determined weekly, and quantities of silage and concentrate offered were adjusted regularly to maintain desired ratios of forage to concentrate. Orts were weighed daily, composited by period, and analyzed for DM and NDF to calculate intakes of DM and NDF.

The cows were cared for according to guidelines of the Canadian Council on Animal Care. Cows were housed in stalls bedded with wood shavings and were turned outside for 1 to 2 h daily, except on days when chewing activities were recorded. Cows were milked in their stalls twice daily, and mean milk yield was calculated using the data from the last 8 d of each period. Milk was sampled in the morning and evening on 2 d during this period, and fat, protein, and lactose contents, weighted for yield, were calculated daily. Means for milk components were calculated as the average of both days. Milk yield on these 2 d was used to calculate 4% FCM and SCM. Milk components were determined by the Alberta Agriculture, Food and Rural Development Milk Testing Laboratory (Edmonton, AB, Canada). Feed efficiency was calculated as the ratio of energy outputs (maintenance, BW change, and milk) to energy consumed as described by Beauchemin et al. (6). Energy for maintenance was calculated as $BW^{0.75}$ (kilograms) × 0.08 (megacalories per kilogram), BW change was assumed to be 5.12 Mcal/kg of gain or 4.92 Mcal/kg of loss, and milk energy was calculated as SCM (kilograms) × 0.75 (megacalories per kilogram).

Chewing Activities

Chewing activities were monitored for approximately 4 d using a strain gauge transducer linked to a computerized data acquisition system (10). In addition to computer records, analog signals from the transducers were recorded continuously using a multichannel chart recorder. Computer records were verified with chart tracings to ensure accurate assessment of eating and ruminating activities. Chewing activities were expressed per unit of DMI, NDF intake, and NDFF intake by dividing minutes or number of chews by mean daily intake for the period.

Digestibility

Twice daily, each cow was offered 30 g/d of barley that had been labeled with chromic oxide to supply 1 g/d of Cr. Approximately 16 fecal samples were collected during an 8-d interval to account for the day-to-day variation. Sampling times differed each day such that the entire 24-h day was represented to account for possible diurnal variation. Fecal samples were dried (55°C), ground to pass a 1-mm screen, and pooled by period for each cow. Concentrations of Cr were determined using atomic absorption spectrometry (30) to calculate DM digestibility.

In Sacco Measurements

Three multiparous cows (square 2) were used for in sacco measurements. A composite sample of barley silage was dried in a forced-air oven at 55°C and ground to pass a 2-mm screen. Five grams of DM were weighed into small bags (10 × 20 cm) made of monofilament Pecap® polyester (pore size, 51 ± 2 μm; B. & S. H. Thompson, Ville Mont-Royal, QC, Canada) and then heat-sealed. Large (20 × 30 cm) mesh retaining sacs with 3- × 5-mm pores that permitted ruminal fluid to percolate freely were placed in the rumen of each cow. Individual polyester bags were soaked in warm water for 10 min, and duplicate bags were added to the retaining sacs representing 3, 6, 9, 12, 24, 36, 48, 72, 96, and 120 h of incubation. All bags were removed at the end of the incubation period, washed under running tap water, and then machine washed in cold water until the effluent was clear. Bags were dried at 55°C for 48 h.

The kinetics of DM disappearance in sacco were estimated using nonlinear least squares (PROC NLIN of SAS) (24). For each cow and period, the

TABLE 1. Composition of ingredients.

Composition	Barley concentrate		Corn concentrate		Protein supplement		Barley silage	
	(% of DM)[1]							
Ingredient								
Barley, steam rolled	74.63		0		0		. . .	
Corn, steam rolled	0		74.70		0		. . .	
Barley, ground	14.43		0		0		. . .	
Corn, ground	0		5.88		0		. . .	
Corn gluten meal (60% CP)	2.47		0		31.26		. . .	
Blood meal	2.50		0.31		31.60		. . .	
Corn distillers dried grains	0		0		31.60		. . .	
Soybean meal	0		13.09		0		. . .	
Dicalcium phosphate	1.36		1.44		0		. . .	
Calcium carbonate	0		0		0.33		. . .	
Monophosphorus	0		0		0.55		. . .	
Mineral and vitamin premix[2]	1.73		1.73		1.67		. . .	
Pellet binder	1.13		1.11		1.29		. . .	
Molasses, liquid	1.75		1.74		1.70		. . .	
	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Chemical component								
DM, %	86.7	0.7	79.8	1.7	90.4	0.4	42.7	1.5
OM	90.1	0.6	90.8	0.1	92.9	0.2	88.9	0.9
CP	19.4	1.0	19.4	0.4	56.0	0.5	10.5	0.6
RUP	6.8	. . .	6.8	. . .	33.6	. . .	2.1	. . .
NE_L,[3] Mcal/kg of DM	1.85	. . .	1.91	. . .	1.77	. . .	1.32	. . .
NDF	24.7	2.5	15.3	2.0	30.0	5.2	61.4	1.7
ADF	7.5	0.1	5.2	0.1	7.85	0.2	38.3	0.9
Acid detergent lignin	. . .	. . .	. . .	. . .	. . .	. . .	5.6	0.1
Starch	51.3	5.7	NA[4]	NA	9.8	0.7	12.1	3.4
Ca	0.61	. . .	0.65	. . .	0.42	. . .	0.06	0.29
P	0.95	. . .	1.06	. . .	0.76	. . .	0.29	0.01

[1]Excluding DM and NE_L.

[2]Supplied per kilogram of premix: 166,700 IU of vitamin A, 20,850 IU of vitamin D_3, 200 IU of vitamin E, 895 g of NaCl, 5.5 g of Mg, 9.0 g of K, 8.9 g of Zn, 6.75 g of Mn, 1.63 g of Cu, and 28.7 mg of Se.

[3]The NE_L of the concentrate and supplement was calculated from NRC (21) values; the NE_L of forages was estimated.

[4]Analysis not available because of spoilage of the samples.

following model (19) was fitted to the percentage of DM disappearance:

$$y = a + b\,(1 - e^{-c(t - L)}) \text{ for } t > L$$

where

a = soluble fraction (percentage),
b = slowly digestible fraction (percentage),
c = fractional rate of disappearance (percentage per hour),
L = lag time (hours), and
t = incubation time (hours).

Effective ruminal degradability was estimated using the model

$$y = a + b \times [c/(c + k)] \times e^{(-k \times L)}/100$$

where

k = fractional rate of particulate passage (assumed to be 3%/h).

Feed Analysis

Composite samples of all feeds were obtained during each experimental period. Silage was dried to a constant weight in a forced-air oven at 55°C. Analytical DM content of feeds was determined by oven-drying at 135°C; OM was determined by ashing the samples, and CP was determined by the micro-Kjeldahl method (2). The NDF, ADF, and acid detergent lignin (72% H_2SO_4) were determined using methods described by Van Soest et al. (27). Sodium sulfite was used only in the NDF analysis of the protein supplement, and the NDF values were not corrected for ash content. Starch was determined by the enzymatic method described by Herrera-Saldana et al. (16) as modified by our laboratory. Sample size and reagents were reduced to read samples colorimetrically at 490 nm using a plate reader. The enzymatic hydrolysis was extended to 1 h using α-amylase (Termamyl; Novo Nordisk, Bagsvaerd, Denmark), and amyloglucosidase (no. 208-469; Boehringer Mannheim, Laval, QC, Canada) was used rather than glucoamylase. The Ca was determined using atomic absorption spectrophotometry; P was analyzed colorimetrically using an autoanalyzer (2). Concentrations of all nutrients were expressed as a percentage of DM (Tables 1 and 2).

Particle size of composite barley silage was determined by wet-sieving using an oscillating sieve shaker (Analysette 3®; Fritsch, Oberstein, Germany) equipped with a stack of sieves (W. S. Tyler, Inc.,

TABLE 2. Composition of diets.[1]

Composition	Barley Low	Barley Medium	Barley High	Corn Low	Corn Medium	Corn High
	(% of DM)[2]					
Feedstuff						
Barley concentrate	58.79	47.86	21.10	0	0	0
Corn concentrate	0	0	0	58.79	47.86	21.10
Protein supplement	10.44	12.19	13.94	10.44	12.19	13.94
Barley silage	30.77	39.95	64.96	30.77	39.95	64.96
Chemical component[3]						
DM, %	72.1	67.7	55.4	68.0	64.4	54.0
OM	90.0	90.0	89.6	90.5	90.3	89.8
CP	20.5	20.3	18.7	20.5	20.3	18.7
RUP	8.2	8.2	7.5	8.2	8.2	7.5
NE_L,[4] Mcal/kg of DM	1.68	1.63	1.49	1.71	1.66	1.51
NDF	36.6	40.0	49.3	31.0	35.5	47.3
NDFF	18.9	24.5	39.9	18.9	24.5	39.9
ADF	17.0	19.9	27.6	15.6	18.7	27.1
Starch	34.9	30.6	20.0	NA[5]	NA	NA
Ca	0.42	0.37	0.22	0.44	0.38	0.23
P	0.73	0.66	0.50	0.79	0.72	0.52

1Low = Low percentage of NDF from forage (NDFF) (19 to 20% NDF), medium = medium percentage of NDFF (24 to 26% NDF), and high = high percentage of NDFF (40 to 42% NDF).

[1]Excluding DM and NE_L.

[3]Calculated from Table 1.

[4]Estimated NE_L based on NRC (21) values.

[5]Analysis not available because of spoilage of the samples.

TABLE 3. Particle size distribution of barley silage.[1]

Item	$\overline{X}$	SD
Theoretical chop length, mm	10	. . .
Geometric length, mm		
With soluble fraction	2.85	0.09
Without soluble fraction	9.93	0.14
	(cumulative % of DM)	
Screen size, mm		
13.20	24.5	0.3
6.70	35.8	0.7
4.75	44.1	0.6
3.35	58.1	0.5
1.18	65.3	0.6
0.15	72.8	0.9

[1]Determined by wet-sieving.

Mentor, OH) arranged in descending mesh size. About 30 g of wet silage in 1 L of water were poured onto the top screen, and the stack of sieves was shaken until the distribution of material on the sieves did not change (about 10 min). During this time, the water was recirculated through the sieves; the lid was equipped with nozzles to provide a light spray, and the bottom pan contained an outlet to the reservoir. The fraction of DM retained on each sieve (13.2, 6.7, 4.75, 3.35, 1.18, and 0.15 mm) was determined, and the geometric mean size by mass was calculated (1).

Statistical Analysis

Data on several variables, including DMI, BW, milk, digestibility, and chewing, were analyzed using the general linear models procedure of SAS (24); group, cow within group, period within group, concentrate, NDFF, and the interaction of concentrate and NDFF were terms in the model (25). The effect of group was assumed to be the effect of parity. Initially, interactions between group (parity) and concentrate and interactions between group and NDFF, as well as the three-way interaction, were also included in the model. Because these interactions were not significant for most variables, they were subsequently removed to increase the error degrees of freedom. Least squares means for group (parity) are presented in the tables. In contrast, the interaction of concentrate and NDFF was significant for a number of variables; therefore, least squares means for the interaction are presented. Treatment means for NDFF were compared using the PDIFF option of the general linear models procedure of SAS only when the main effect or two-way interaction was significant at $P < 0.05$ (24). In addition, relationships of milk variables and NDF percentage were examined by including either actual dietary NDF intake or NDFF intake of individual cows, expressed as kilograms per day or as a percentage of DMI, as continuous linear (1 df) and quadratic (1 df) variables in the model. Significance was declared at $P < 0.05$ unless otherwise stated.

TABLE 4. Effect of concentrate type and percentage of NDF from forage (NDFF) on BW and nutrient intake.[1]

	Parity[2]			Barley			Corn				Effect[3]			
Variable	PP	MP	SE	Low	Medium	High	Low	Medium	High	SE	P	C	F	C × F
											P			
BW, kg	537.5	619.5	1.9	579.4	574.8	576.3	582.3	581.9	576.3	3.4	**	NS[4]	NS	NS
BW Gain, kg/d	0.30	0.17	0.12	0.41	0.17	–0.03	0.54	0.32	–0.01	0.21	NS	NS	†	NS
DMI, kg/d	16.8	20.2	0.2	19.7[a]	19.3[a]	17.0[b]	19.2[a]	19.0[a]	16.7[b]	0.4	**	NS	**	NS
DMI, % of BW	3.12	3.27	0.03	3.40[a]	3.34[a]	2.96[b]	3.30[a]	3.29[a]	2.90[b]	0.06	**	NS	**	NS
Concentrate,														
% of DMI	53.0	54.8	0.4	69.2[a]	61.1[b]	34.5[c]	67.7[a]	57.9[b]	32.7[c]	0.8	**	**	**	NS
NE_L, Mcal/d	24.22	29.85	0.3	30.98[a]	28.93[b]	21.78[c]	30.61[a]	28.68[b]	21.25[c]	0.59	**	NS	**	NS
NDF, % of BW	1.31	1.30	0.02	1.25[c]	1.37[b]	1.48[a]	1.06[c]	1.24[b]	1.42[a]	0.03	NS	**	**	†
NDF, % of DMI	42.2	39.9	0.3	36.7[c]	40.9[b]	49.9[a]	32.0[c]	37.6[b]	49.0[a]	0.5	**	**	**	**
NDFF, % of DMI	29.6	27.3	0.3	19.0[c]	24.0[b]	40.2[a]	20.0[c]	25.9[b]	41.6[a]	0.5	**	**	**	NS
ADF, % of DMI	21.7	21.0	0.1	17.0[c]	19.6[b]	27.8[a]	16.2[c]	19.5[b]	27.9[a]	0.2	**	NS	**	NS

[a,b,c]Subcolumn means within row and treatment category with different superscripts differ ($P < 0.05$).

[1]Low = Low percentage; of NDFF (19 to 20% NDF), medium = medium percentage of NDFF (24 to 26% NDF), and high = high percentage of NDFF (40 to 42%).

[2]PP = Primiparous; MP = multiparous.

[3]P = Main effect of parity, C = main effect of concentrate type, and F = main effect of percentage of NDFF.

[4]$P > 0.10$.

†$P < 0.10$.

**$P < 0.01$.

Kinetics of DM disappearance were analyzed using a model similar to that used for production variables but without group or period effects, which resulted in 10 df for the error term.

RESULTS AND DISCUSSION

Analysis of particle size indicated that the barley silage was relatively coarsely chopped (Table 3); thus, the forage used in this study was considered to be a relatively effective fiber source. The geometric mean particle length of 9.93 mm was considered to be above the threshold amount that was known to reduce rumination time and cause milk fat depression (3, 7). Therefore, silage chop length was not likely a confounding factor in this study.

All diets used in this study contained sufficient total NDF and NDFF according to NRC (21) recommendations. The recommendation of 25 to 28% total NDF in the diet equates to 18.7 to 21% NDFF, assuming that forages contributed 75% of the fiber. In this study, the diets based on barley and corn used were formulated to contain the same amount of NDFF, but small variations in intake resulted in the consumption of slightly higher concentrations of NDFF (Table 4). Total NDF concentrations of the diets were consistent with formulated percentages and ranged from 32 to 50% of DMI. As expected, the higher NDF content of the barley concentrate resulted in higher total NDF percentages for barley diets than for corn diets.

Intakes of DM and NE_L were similar for barley and corn diets (Table 4), and, consequently, milk yield was not affected by type of grain (Table 5). As the ratio of forage to concentrate of the diet was increased to supply more forage fiber, DMI and NE_L intake decreased ($P < 0.05$), especially between diets with a medium percentage of NDFF and diets with a high percentage of NDFF (Table 4). As a result, mean milk yield decreased as forage in the diet increased, but only the diet with the highest percentage of NDFF was significantly different from the other concentrations of forage (Table 5). A significant quadratic relationship was observed for milk yield and the actual amount of NDFF consumed, expressed either as a percentage of DMI ($P_L = 0.12$, where L = linear; $P_Q = 0.04$, where Q = quadratic) or as kilograms per day ($P_L = 0.02$; $P_Q = 0.002$; data not shown); there was no effect ($P > 0.05$) of concentrate source. Milk yield declined when NDFF exceeded 24 to 26%, or about 5 kg/d, which corresponded to a substantial decline in energy intake (Table 4). In comparison, linear and quadratic relationships between milk yield and total dietary NDF intake, expressed as a percentage of DMI or as kilograms per day (data not shown), were not statistically significant. Use of NDFF rather

TABLE 5. Effect of concentrate type and percentage of NDF from forage (NDFF) on milk yield and composition.[1]

	Parity[2]			Barley			Corn				Effect[3]			
Variable	PP	MP	SE	Low	Medium	High	Low	Medium	High	SE	P	C	F	C × F
Yield, kg/d														
Milk	22.4	28.3	0.4	27.5[a]	26.6[a]	23.1[b]	26.1[a]	25.7[a]	23.2[b]	0.6	**	NS[4]	**	NS
4% FCM	20.2	23.9	0.4	23.1[a]	23.7[a]	20.2[b]	23.0[a]	22.3[a]	19.8[b]	0.6	**	NS	**	NS
SCM	20.3	23.9	0.3	23.7[a]	23.8[a]	19.9[b]	23.1[a]	22.4[a]	19.6[b]	0.6	**	NS	**	NS
Fat	0.75	0.83	0.2	0.79[ab]	0.87[a]	0.73[b]	0.84[a]	0.80[a]	0.71[b]	0.03	**	NS	**	NS
Protein	0.70	0.88	0.1	0.91[a]	0.86[a]	0.69[b]	0.82[a]	0.80[a]	0.68[b]	0.02	**	**	**	NS
Lactose	1.09	1.33	0.2	1.35[a]	1.27[a]	1.08[b]	1.24[a]	1.24[a]	1.08[b]	0.03	**	†	**	NS
Composition, %														
Fat	3.38	2.91	0.06	2.87[b]	3.26[a]	3.19[a]	3.26	3.13	3.16	0.10	**	NS	NS	*
Protein	3.16	3.10	0.01	3.24[a]	3.21[a]	3.00[b]	3.18[a]	3.13[a]	3.00[b]	0.02	**	*	**	NS
Lactose	4.89	4.63	0.01	4.77[a]	4.79[a]	4.69[b]	4.79[a]	4.81[a]	4.73[b]	0.02	**	†	**	NS
Feed efficiency[5]	1.09	0.97	0.02	0.94[b]	0.98[b]	1.12[a]	0.97[b]	0.99[b]	1.16[a]	0.04	**	NS	**	NS

[a,b]Subcolumn means within row and treatment category with different superscripts differ ($P < 0.05$).

[1]Low = Low percentage of NDFF (19 to 20% NDF), medium = medium percentage of NDFF (24 to 26% NDF), and high = high percentage of NDFF (40 to 42%).

[2]PP = Primiparous; MP = multiparous.

[3]P = Main effect of parity, C = main effect of concentrate type, and F = main effect of percentage of NDFF.

[4]$P > 0.10$.

[5]NE_L Outputs (i.e., maintenance + BW change + milk)/NE_L inputs (i.e., feed).

†$P < 0.10$.

*$P < 0.05$.

**$P < 0.01$.

than total NDF was, therefore, more useful in formulating diets for maximal milk yield.

The optimum concentration of NDFF can be considered as that which maximizes NE_L intake, and consequently, milk yield (6). Briceno et al. (11) also concluded that NE_L intake and DMI were the most important dietary factors that affected milk yield, even though NE_L values are estimated rather than chemically determined values. In the present study, diets formulated above 24 to 26% NDFF resulted in NE_L intakes that were less than those required to sustain a milk yield of 25 kg/d; consequently, milk yield was decreased (Table 5). This concentration of NDFF represented a total NDF intake of 1.37% of BW for barley diets and 1.24% of BW for corn diets. The results from the corn diets confirmed that the 1.20% of BW that was reported by Mertens (20) was the maximum amount of fiber that the cow in midlactation could consume without decreasing milk yield below genetic potential.

Others (20) have considered optimum NDF content of the diet in terms of maximum FCM rather than maximum milk yield. Relationships between FCM and NDF were similar to those observed for milk yield. Mean FCM yield was significantly lower for cows fed diets with a medium percentage of NDFF than for those fed a high percentage of NDFF; there was no difference between results with corn and barley concentrates (Table 5). A significant curvilinear relationship was observed for FCM and actual NDFF intake, expressed either as a percentage of DMI (P_L = 0.16; P_Q = 0.06) or as kilograms per day (P_L = 0.08; P_Q = 0.02), but relationships between FCM and total dietary NDF intake, expressed as a percentage of DMI or as kilograms per day (data not shown), were not statistically significant.

Although the optimal concentration of fiber in the diet may be considered in terms of maximum milk or FCM yield, it is well known that the dairy cow needs some dietary fiber. The NRC (21) recommendations for dietary NDF are considered to be minimum concentrations that are necessary to prevent milk fat depression. Unlike milk yield and FCM, the fat content of milk was affected by the percentage of NDFF (P = 0.03) in barley and corn diets (Table 5). The diet based on barley with the lowest percentage of NDFF caused milk fat to decline. Numerous other studies (13, 15, 28, 29) have reported lower milk fat for cows fed barley than for cows fed corn, although those comparisons were mainly between diets that differed in NDFF content.

Fat content was somewhat lower than expected for cows fed the diets with the medium and high percentages of NDFF for both grains. In previous studies (4,

TABLE 6. Effect of concentrate type and percentage of NDF from forage (NDFF) on time spent chewing.[1]

	Parity[2]			Barley			Corn				Effect[3]			
Variable	PP	MP	SE	Low	Medium	High	Low	Medium	High	SE	P	C	F	C × F
Eating														
min/d	322	304	6	268^{c}	311^{b}	350^{a}	287^{b}	314^{b}	348^{a}	10	*	NS[4]	**	NS
min/kg of DM	19.5	15.4	0.3	13.9^{c}	16.5^{b}	20.9^{a}	15.3^{b}	16.7^{b}	21.2^{a}	0.5	**	NS	**	NS
min/kg of NDF	46.5	38.5	0.9	38.0	40.2	41.7	47.8	44.2	43.2	1.6	**	**	NS	*
min/kg of NDFF	69.3	59.9	1.9	73.2^{a}	70.4^{a}	52.0^{b}	76.6^{a}	64.4^{b}	51.1^{c}	3.4	**	NS	**	NS
Ruminating														
min/d	474	511	6	499^{b}	510^{ab}	538^{a}	426^{c}	458^{b}	523^{a}	11	**	**	**	*
min/kg of DM	28.5	25.9	0.3	25.8^{b}	27.0^{b}	32.1^{a}	22.6^{c}	24.3^{b}	31.7^{a}	0.6	**	**	**	†
min/kg of NDF	68.4	65.0	1.2	70.2^{a}	66.1^{ab}	64.2^{b}	70.5^{a}	64.5^{b}	64.7^{ab}	2.0	†	NS	*	NS
min/kg of NDFF	102.6	102.8	3.2	135.6^{a}	117.1^{b}	80.0^{c}	113.3^{a}	93.9^{b}	76.4^{c}	5.5	NS	**	**	NS
Chews/d ($\times 10^3$)	32.4	32.6	0.4	32.9^{b}	34.0^{ab}	35.7^{a}	27.6^{c}	30.1^{b}	34.7^{a}	0.8	NS	**	**	*
Chews/g of DM	1.95	1.66	0.02	1.70^{b}	1.80^{b}	2.13^{a}	1.47^{c}	1.60^{b}	2.11^{a}	0.04	**	**	**	*
Chews/g of NDF	4.65	4.15	0.08	4.65^{a}	4.40^{ab}	4.25^{b}	4.58	4.24	4.29	0.13	**	NS	*	NS
Chews/g of NDFF	6.99	6.56	0.21	8.95^{a}	7.78^{b}	5.29^{c}	7.36^{a}	6.17^{b}	5.07^{c}	0.36	NS	**	**	†

[a,b,c]Subcolumn means within row and treatment category with different superscripts differ ($P < 0.05$).

[1]Low = Low percentage of NDFF (19 to 20% NDF), medium = medium percentage of NDFF (24 to 26% NDF), and high = high percentage of NDFF (40 to 42%).

[2]PP = Primiparous; MP = multiparous.

[3]P = Main effect of parity, C = main effect of concentrate type, and F = main effect of percentage of NDFF.

[4]$P > 0.10$.

†$P < 0.10$.

*$P < 0.05$.

**$P < 0.01$.

6), increased NDF concentration corresponded to a linear increase in milk fat content. In those studies, 25 to 28% NDFF was needed to maintain a milk fat content of 3.5% when barley concentrates were fed. The inconsistency of results from the present study and those from previous studies may relate to differences in the sources of the forages used. Barley silage was the sole source of forage in the present study, but alfalfa hay, orchardgrass hay, and corn silage were the forages used in the previous studies.

Linear and quadratic effects of amount of NDFF consumed or amount of total NDF consumed on milk fat content were not significant.

Lower milk fat for cows fed large quantities of barley than for those fed corn reflects the differences in ruminal digestion characteristics of these carbohydrate sources. Barley, in contrast to corn, is almost entirely fermented in the rumen, which results in low ruminal pH and high molar proportions of propionate (22). Such a low ratio of acetate to propionate usually corresponds with low milk fat percentage (26). Slower ruminal fermentation of corn results in a greater supply of glucose to the duodenum than that resulting from barley diets (18, 26). Thus, the chemical form of glucogenic precursors for milk in high grain barley diets differs from that in corn diets. Nocek and Tamminga (22) analyzed data from 14 experiments to determine the effects of site of starch digestion on milk yield at a constant energy intake. Those researchers concluded that milk yield was maximized by increasing intake of both ruminally available starch and postruminally available starch. Therefore, it is not surprising that the milk yield of cows fed barley and corn diets has been reported to be similar in some studies (13, 15) but different in others (12, 18). Variations in response probably relate to differences in starch intake and site of digestion.

In the present study, protein content of milk was higher ($P = 0.02$) for cows receiving barley than for those receiving corn, and protein content decreased as the concentration of NDFF increased (Table 5). A similar relationship was observed for lactose. Thus, barley diets formulated at low concentrations of forage fiber favor a high yield of milk that is low in fat and high in protein and lactose. The changing consumer demand for milk products that are low in fat and high in protein makes barley a desirable component of dairy cow diets.

The milk fat depression that occurred for cows fed low fiber barley diets was not explained by differences in chewing activities (Table 6). Eating times were similar for cows fed barley or corn, and time spent eating increased as the proportion of forage in the diet increased. Shorter eating times for higher grain diets were consistent with previous findings (5, 9). Characteristics of eating behavior are influenced primarily by physical factors that affect ease of ingestion and mastication (3). Thus, less chewing of high grain diets reflects the greater ease of bolus formation

TABLE 7. Effect of concentrate type and percentage of NDF from forage (NDFF) on rumination behavior.[1]

	Parity[2]			Barley			Corn				Effect[3]			
Variable	PP	MP	SE	Low	Medium	High	Low	Medium	High	SE	P	C	F	C × F
Rumination periods														
Periods/d	16.7	15.1	0.2	16.2	15.8	16.4	15.5	15.6	15.7	0.4	**	†	NS[4]	NS
Duration	28.5	34.8	0.6	31.2	33.4	33.1	28.1[b]	30[b]	34.1[a]	1.0	**	*	**	†
Chews per period	1953	2229	41	2054	2231	2208	1821[b]	1968[b]	2265[a]	71	**	*	**	†
Rumination boluses														
Boluses/d	475	493	7	481[b]	498[b]	536[a]	422[b]	447[b]	522[a]	12	†	**	**	NS
Boluses per period	28.7	33.3	0.5	30.0[b]	32.2[ab]	32.9[a]	27.7[b]	29.2[b]	34[a]	0.9	**	†	**	†
Duration of boluses, s	57.1	59.4	0.6	58.9	58.4	57.2	58.8	58.9	57.2	1.0	**	NS	NS	NS
Chews per bolus	68.0	66.1	0.6	67.5	68.1	66.4	66.2	67.6	66.3	1.1	*	NS	NS	NS

[a,b]Subcolumn means within row and treatment category with different superscripts differ ($P < 0.05$).

[1]Low = Low percentage of NDFF (19 to 20% NDF), medium = medium percentage of NDFF (24 to 26% NDF), and high = high percentage of NDFF (40 to 42%).

[2]PP = Primiparous; MP = multiparous.

[3]P = Main effect of parity, C = main effect of concentrate type, and F = main effect of percentage of NDFF.

[4]$P > 0.10$.

†$P < 0.10$.

*$P < 0.05$.

**$P < 0.01$.

and swallowing for grains versus forages. Both concentrates were apparently consumed with similar ease, and eating times at similar ratios of forage to concentrate were similar.

In contrast to eating, rumination time and chews were higher for cows fed barley diets than for cows fed corn diets ($P < 0.001$; Table 6). The greater rumination activity of cows fed barley was a result of more rumination periods ($P = 0.06$) of longer duration ($P = 0.03$; Table 7). When rumination time and number of chews were expressed on the basis of total dietary NDF intake, rumination activities were similar for barley and corn diets (Table 6). Thus, higher rumination activity for barley than for corn might have been due to the higher NDF content of barley. Alternatively, cows fed barley might have spent more time ruminating because of reduced digestibility of forage NDF (6); low ruminal pH and decreased cellulolytic activity promoted more rumination of forage fiber. Because ruminal and total tract digestibilities of barley silage were similar for barley and corn diets (Table 8), the increased rumination of barley diets was likely due to its higher NDF content rather than to increased chewing of forage. This conclusion is consistent with results from a study in which beef cattle fed 100% grain ruminated twice as much when fed barley as when fed corn (8). The higher rumination time for cows fed barley might be due to the hulls, as well as a more resistant pericarp, resulting in a greater proportion of ingested intact kernels.

Increased rumination for higher forage diets as observed in this experiment is well documented (5, 6, 9). The need to ruminate is related to the increased intake of slowly digestible and indigestible feed. However, the significant interaction between concentrate source and concentration of NDFF for rumination time and chews indicated that the chewing activity of cows differed as the proportion of forage increased in the barley and corn diets. The concentration of forage fiber influenced rumination time required for barley diets less than it influenced rumination time for corn diets; as the amount of barley silage in the diet increased from 31 to 65%, rumination of barley diets only increased by 39 min but rumination of corn diets increased by 97 min (Table 6). Except when a digestive upset occurred, the ratio of forage to concentrate had only minor effects on rumination time when concentrates were primarily barley, because of the high NDF content of barley.

The percentage of NDFF in the diet influenced the ruminal digestion kinetics of silage DM, although these differences were not evident for total tract DM digestibility (Table 8). Rate of DM disappearance nearly doubled as NDFF increased from low to high. Consequently, effective ruminal degradability also increased as the percentage of forage in the diet increased. Improved fiber digestibility was undoubtedly the result of a higher ruminal pH and more favorable ruminal environment. No effects of diet were observed for the soluble or slowly digestible fractions or for the

TABLE 8. Effect of concentrate type and percentage of NDF from forage (NDFF) on ruminal and total tract digestibility of DM.[1]

	Parity[2]			Barley			Corn				Effect[3]			
Variable	PP	MP	SE	Low	Medium	High	Low	Medium	High	SE	P	C	F	C × F
Total tract digestibility, %	70.2	67.1	0.5	69.9	68.8	68.3	68.4	69.5	67.0	0.9	**	NS[4]	NS	NS
Ruminal DM disappearance														
Soluble fraction, %	NM[5]	NM	NM	34.9	33.6	31.5	33.6	33.0	33.5	1.5	NM	NS	NS	NS
Slowly digestible fraction, %	NM	NM	NM	33.9	37.5	35.6	37.2	36.9	39.3	2.3	NM	NS	NS	NS
Extent, %	NM	NM	NM	68.8	71.1	67.1	70.8	69.9	72.8	2.1	NM	NS	NS	NS
Rate, %/h	NM	NM	NM	2.49[b]	3.22[b]	5.32[a]	2.53	3.78	3.96	0.49	NM	NS	**	NS
Lag, h	NM	NM	NM	0	0	0	0	0	0	. . .	NM	. . .	. . .	. . .
ERD,[6]%	NM	NM	NM	50.0[b]	52.8[ab]	53.8[a]	50.1[b]	53.5[ab]	55.7[a]	1.2	NM	NS	**	NS

[a,b]Subcolumn means with row and treatment category with different superscripts differ ($P < 0.05$).

[1]Low = Low percentage of NDFF (19 to 20% NDF), medium = medium percentage of NDFF (24 to 26% NDF), and high = high percentage of NDFF (40 to 42%).

[2]PP = Primiparous; MP = multiparous.

[3]P = Main effect of parity, C = main effect of concentrate type, and F = main effect of percentage of NDFF.

[4]$P > 0.10$.

[5]Not measured.

[6]Effective ruminal degradability.

**$P < 0.01$.

extent of disappearance. Higher silage digestibility for higher forage diets was consistent with the observed improvement in feed efficiency, which was measured as NE_L outputs per unit of NE_L consumed (Table 5).

The design of this experiment also provided a comparison between primiparous and multiparous cows. Primiparous cows weighed less, consumed less DM and energy (Table 4), yielded less milk of higher fat content, and had a higher feed efficiency than did multiparous cows (Table 5). Although primiparous cows spent more time eating and less time ruminating than did multiparous cows (Table 6), primiparous cows actually spent more time eating and ruminating per kilogram of DM or NDF as was reported previously (9). Because longer chewing times corresponded to more chews, younger cows apparently chewed feed more extensively than did multiparous cows. The results from this study supported the suggestion that younger cows may have needed greater access time to feed and less competition at the manger to maximize feed intake because these cows chewed more slowly and more thoroughly (9). The thorough chewing activity of younger cows might have partially accounted for the higher DM digestibility (Table 8), which is consistent with the higher feed efficiency of younger cows.

CONCLUSIONS

When compared at the same concentration of NDFF, barley diets required longer rumination times than did corn. Rumination time was related to total dietary NDF rather than to NDFF. Despite longer rumination time, more fiber from forage sources was needed in barley diets than in corn diets to avoid milk fat depression, most likely because of the more rapid fermentation rate of barley grain. For cows fed barley diets, lower NDFF depressed milk fat content, but, for cows fed corn diets, the milk fat content was similar when the diets contained 19.5 or 25% NDFF.

A quadratic relationship was observed between milk yield and NDFF, and there was no effect of concentrate type. Milk yield and FCM were maximal when diets were formulated to supply 19.5 to 25% NDFF, but were reduced when NDFF was increased further because of a decline in energy intake.

In the context of current and proposed milk component pricing systems in Canada, milk with a lower ratio of fat to protein can give higher returns to producers. Therefore, milk fat depression may no longer be a valid criterion by which to assess minimum fiber concentrations. The minimal amount of fiber in the dairy cow diet, then, must be considered in terms of maintaining healthy ruminal function. The minimum amount is less than that used in this experiment because no incidence of lameness or subacute acidosis was observed. Further research must be conducted to determine the long-term effects of minimum fiber diets on the health and longevity of cows. The decision to formulate diets in excess of this minimum amount could then be based on the relative costs of concentrates and forage and the revenue from milk and milk components.

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