Effects of Particle Size of Alfalfa-Based Dairy Cow Diets on Chewing Activity, Ruminal Fermentation, and Milk Production¹

K. A. Beauchemin, W. Z. Yang, and L. M. Rode²

Livestock Sciences Section, Research Centre
Agriculture and Agri-Food Canada,
Lethbridge, AB, T1J 4B1, Canada

ABSTRACT

Effects of forage particle size measured as physically effective NDF and ratio of alfalfa silage to alfalfa hay of diets on feed intake, chewing activity, particle size reduction, salivary secretion, ruminal fermentation, and milk production of dairy cows were evaluated using a 4×4 Latin square design with a 2×2 factorial arrangement of treatments. The diets consisted of 60% barley-based concentrate and 40% forage, comprised either of 50:50 or 25:75 of alfalfa silage:alfalfa hay, and alfalfa hay was either chopped or ground. Various methods were used to determine physically effective NDF content of the diets. Cows surgically fitted with ruminal and duodenal cannulas were offered ad libitum access to these total mixed diets. The physically effective NDF content of the diets was significantly lower when measured using the Penn State Particle Separator than when measured based on particles retained on 1.18-mm screen. Intake of DM was increased by increasing the ratio of silage to hay but was not affected by physically effective NDF content of diets. Eating time (hours per day) was not affected by the physically effective NDF content of diets, although cows spent more time eating per unit of DM or NDF when consuming high versus low alfalfa hay diets. Ruminating time (hours per day) was increased with increased physically effective NDF content of the diets. Rumen pH was affected more by changing dietary particle size than altering the ratio of silage to hay. Feeding chopped hay instead of ground hay improved ruminal pH status: time during which ruminal pH was above 6.2 increased and time during which ruminal pH was below 5.8 decreased. Milk production was increased by feeding higher concentrations of alfalfa silage due to increased DM intake, but was not

affected by dietary particle size. Feed particle size, expressed as mean particle length or physically effective NDF was moderately correlated with ruminating time but not with eating time. Although physically effective NDF and chewing time were not correlated to mean rumen pH, they were negatively correlated to the area between the curve and pH 5.8, indicating a positive effect on reducing the risk of acidosis. Milk fat content was correlated to rumen pH but not to physically effective NDF or chewing activity. These results indicate that increasing physically effective NDF content of the diets increased chewing activity and improved rumen pH status but had limited effect on milk production and milk fat content.

(**Key words:** physically effective NDF, chewing behavior, rumen pH, dairy cow)

Abbreviation key: AH = alfalfa hay, AS = alfalfa silage, AS:AH = ratio of alfalfa silage to alfalfa hay, FPS = forage particle size, MPL = mean particle length, **pe** = physically effective, **pef** = physical effectiveness factor, **pef_M** = physical effectiveness factor from tabular values of chewing time, **pef_{P>1.18}** = physical effectiveness factor determined as a percent of DM remaining on a 1.18-mm screen, **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, **peNDF_M** = physically effective NDF measured as the NDF content of the TMR multiplied by **pef_M**, **peNDF_{P>1.18}** = physically effective NDF measured as the NDF content of the TMR multiplied by **pef_{P>1.18}**, **peNDF_{PS}** = physically effective NDF measured as the NDF content of the TMR multiplied by **pef_{PS}**, **PSPS** = Penn State Particle Separator.

INTRODUCTION

To meet the energy requirements of high producing lactating dairy cows, diets typically contain relatively high proportions of concentrate and high quality forages. The trend is to feed diets that are relatively low in fiber. While this practice encourages maximal milk production, it can also lead to one or more of a variety

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Corresponding author: K. A. Beauchemin; e-mail: beauchemin@agr.gc.ca.

¹Contribution number: 38701057.

²Current address: Rosebud Technologies Development, Ltd., 3302 Beauvais Pl. S., Lethbridge, AB, T1K 3J5, Canada.

of metabolic disorders, including subclinical ruminal acidosis, reduced fiber digestion, milk fat depression, displaced abomasum, laminitis, and fat-cow syndrome (NRC, 2001). Therefore, adequate particle length of forages is necessary for proper ruminal function as coarse particles stimulate chewing activity and hence increase saliva output.

Alfalfa forage, conserved as silage (**AS**) or hay (**AH**), is a major component of diets fed to lactating dairy cows. Alfalfa has become a popular forage for silage because of its high DM yield and CP content. Cows can consume large quantities of alfalfa and produce more milk (Nelson and Satter, 1990) when silage is fed as the sole source of forage because NDF is relatively low and is digested rapidly. However, AS is smaller in particle size than long AH, is less brittle and more pliable than hay, and is hydrated. These attributes might reduce effective fiber content of AS and consequently reduce chewing activity predisposing cows to ruminal acidosis. Several studies showed that supplementation of AS-based diets with AH increased milk production as a result of increasing ruminating time, improving rumen function, and therefore enhancing the digestion of nutrients (Santini et al., 1983; Beauchemin and Buchanan-Smith, 1989).

In addition, the concept of physically effective (**pe**) fiber was recently 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 physically effective fiber (**peNDF**) of feeds can be measured as the NDF content of feeds multiplied by the physically effective factor (**pef**), which can be determined either as the proportion of the feed retained on a 1.18-mm sieve using a dry sieving technique (Mertens, 1997) or as the sum of the DM retained on the two sieves of the Penn State Particle Separator (**PSPS**; Lammers et al., 1996). However, neither system has been adequately validated and there is very limited information to establish the requirements of **peNDF** for dairy cows and to determine the **peNDF** values of feeds.

The objectives of this study were to evaluate the effects of **peNDF** content of alfalfa-based diets on feed intake, chewing activity, ruminal fermentation pattern, and milk production and composition by dairy cows. The **peNDF** contents of the diets were determined by multiplying the NDF content of the diets by **pef**. The **pef** was measured using various methods including the **PSPS**, the tabular values from Mertens (2000), or the proportion of DM retained on a 1.18-mm sieve. In addition, particle size of diets differed by altering the ratio of AS to AH (**AS:AH**) and using AH that was either chopped or ground.

MATERIALS AND METHODS

Forages

Alfalfa was harvested during the second cutting in a midflowering stage and then preserved as silage in large silo bags (200-tonne capacity). A forage harvester (model 5830; John Deere, West Bend, WI), equipped with a 37-tooth sprocket and 8 knives, was used to obtain silage chopped at a theoretical length of 10 mm. Once the silage was preserved and a chemical analysis was determined, a second-cutting AH of similar quality was purchased for the study. The AH was preserved in small rectangular bales. The AH was coarsely chopped by using a bale processor without screen attachment (Agri-Metal bale processor) driven by a 90 Hp tractor. The amount required for the whole experiment was prepared and stored indoors in the feed processing facility. The ground AH was prepared as needed by grinding the chopped AH through a 4-mm screen.

Forages (AS, chopped or ground AH) were sampled once a week with approximately 1 kg of each forage obtained. Before sampling, the piles of chopped and ground hay were turned manually using a pitch fork to minimize layering and possible separation of small particles. The DM content was determined by oven-drying at 55°C for 48 h. The samples were then composited by each experimental period. Chemical composition and particle size distributions of the forages were determined on each composited sample.

Cows and Diets

Four lactating Holstein cows that were surgically 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). The duodenal cannulas were T-type and placed proximal to the bile and pancreatic ducts approximately 10-cm distal to the pylorus. At the start of the experiment, the cows averaged 655 ± 79 kg of BW and 127 ± 38 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 0800, 1500, and 1800 h for ad libitum intake. Cows were weighed at approximately 1030 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).

The experimental design was a 4×4 Latin square with four 21-d periods and a 2×2 factorial arrangement of treatments: AS:AH (high vs. low, 50:50 vs.

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

Item	Diets (alfalfa silage:alfalfa hay)	
	50:50	25:75
Ingredients, %		
Alfalfa silage ¹	19.7	10.2
Alfalfa hay ¹	19.7	29.5
Steam-rolled barley grain ¹	46.1	45.5
Corn gluten meal	3.01	1.94
Heat-treated canola meal (Alberta Gold)	1.70	2.66
Soybean meal	4.51	4.36
Beet molasses	0.97	0.97
Urea	—	0.29
Calcium carbonate	0.78	0.77
Dicalcium phosphate	0.39	0.39
Monophosphate	0.29	0.29
Vitamin and mineral premix ²	1.94	1.94
Canola oil	0.82	0.97
Binding agent (Aka)	0.19	0.19
Chemical, % of DM		
DM	68.3	77.6
OM	91.4	91.3
CP	18.0	18.5
NDF	36.1	36.0
NDF from forages	19.5	18.6
Starch	29.5	28.7
NE _L , Mcal/kg ³	1.58	1.59

¹Chemical composition of alfalfa silage, alfalfa hay, and barley grain (DM basis) was 89.8, 90.8, and 97.7% for OM; 55.2, 52.3, and 25.2% for NDF; 48.0, 42.5, and 6.7% for ADF; 16.6, 17.7, and 13.9 % for CP, respectively.

²Contained 51.97% NaCl, 35.98% Dynamate7 (Pitman Moore, Inc., Mundelein, IL; 18% K, 11% Mg, 22% S, 1000 mg Fe/kg), 2% ZnSO₄·H₂O, 2.4% MnSO₄·4H₂O, 0.01% CoSO₄·6H₂O, 0.009% Na₂SeO₃, 0.012% ethylenediamine dihydroiodide, 0.8% CuSO₄·5H₂O, 680,000 IU/kg of vitamin A, 160,000 IU/kg of vitamin D and 2,000 IU/kg of vitamin E.

³Estimated from NRC (1989).

25:75) combined with particle size of the hay (FPS). The diets were formulated using the Cornell-Penn-Miner System (CPMDairy, Version 1.0) to supply adequate metabolizable energy and protein for a 650-kg cow producing 30 kg/d of milk with 3.5% fat and 3.2% protein (Table 1). The diets consisted of 60% barley-based concentrate and 40% forage. Differences in mean particle length and the pef of the diets were created by manipulating the AS:AH and particle size of the AH (Tables 2 and 3).

Barley grain obtained from one source was used throughout the experiment. The barley was first screened to remove chaff and small kernels and then steam-rolled to an optimum degree of rolling for dairy cows as described by Yang et al. (2000), which was a processing index of 65%. Processing index was defined as the ratio of the volume weight of the barley after processing to its volume weight before processing.

Each period consisted of 11-d of adaptation to diets and 10-d of experimental measurements consisting of chewing activity, salivary secretion during eating, particle size distribution of feed and ingesta, ruminal fermentation characteristics, feed intake, and milk production and composition.

Chewing Activities, Salivary Secretion, and Particle Size Distribution

Chewing activities of the four cows were monitored visually every 5 min for a 24-h period from the 13th to 14th day of the experimental period. The assumption was made that the particular chewing activity persisted for the entire 5-min period between each visual observation. Chewing activities were expressed as total hours for the 24-h period or on the basis of DMI and NDF intake by dividing minutes of eating or ruminating by intake.

Saliva secretion was measured by collecting boluses from the cardia as the cow was eating during the 3 pm feeding on the 17th day of the period. To facilitate sampling, the rumen was partially emptied to expose the cardia. The entire swallowed material, including boluses and saliva, were collected using a plastic bag mounted on a wire hoop inserted through the rumen cannula. Five sequential collections were made by collecting for 2 min at 3-min intervals. Each sample of masticate was weighed and divided into two subsamples: one was dried in an oven at 55°C for 48 h to determine DM content, and the other was pooled by

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

Item	Alfalfa silage	Alfalfa hay		SE
		Chopped	Ground	
Penn State Particle Separator				
DM retention on sieve, %				
Top, 19-mm	4.7 ^b	24.8 ^a	0.0 ^c	1.8
Middle, 8-mm	68.7 ^a	24.7 ^b	0.6 ^c	1.4
Bottom	26.7 ^c	50.5 ^b	99.4 ^a	2.8
pef _{PS} ¹ , %	73.4 ^a	49.5 ^b	0.6 ^c	2.70
pef _M ² , %	85	80	40	—
pef _{P>1.18} ³ , %	66.0 ^a	53.5 ^b	36.0 ^c	0.8
Wet sieving				
DM retained on sieve, %				
9.50	19.7 ^a	18.6 ^a	0.0 ^b	0.7
6.70	10.6 ^a	6.2 ^b	0.0 ^c	0.1
3.35	20.5 ^a	14.9 ^b	2.8 ^c	0.3
1.18	13.0 ^b	9.9 ^b	28.3 ^a	0.8
0.60	3.4 ^c	7.6 ^b	11.7 ^a	0.4
0.15	7.7 ^b	15.1 ^{ab}	20.9 ^a	3.5
Not retained	25.1 ^b	27.8 ^{ab}	36.4 ^a	3.5
MPL ⁴ , mm	7.93 ^a	5.67 ^b	2.22 ^c	0.13

^{a,b,c}Means within the same row not followed by the same letter differ ($P < 0.05$).

¹Physical effectiveness factor determined as the proportion of dry matter retained by both sieves of the Penn State Particle Separator.

²Physical effectiveness factor based on chewing activity determined by Mertens (1997).

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

⁴Fifty percent of the particles are greater or less than this length.

cow and stored frozen at -20°C for particle size analysis. Saliva output was estimated as the additional moisture content of the boluses relative to the moisture content of the diet which was sampled at the same time as the bolus collection. Salivation rate (milliliter per minute) was calculated for each individual collec-

tion as the ratio between the total amount of saliva obtained and the duration of that collection. Ensalivation (milliliter per gram of DMI) of the feed was calculated as the amount of saliva added per gram of feed ingested. The daily saliva production during eating was estimated either by multiplying the eating saliva-

Table 3. Particle size distribution and physical effectiveness factors of diets.

Item	Diets ¹				SE	Effect ² , <i>P</i> <		
	AS:AH 50:50		AS:AH 25:75			AS:AH	FPS	AS:AH × FPS
	CH	GH	CH	GH				
Feed retention on sieve, %								
Top, 19-mm	9.4	0.8	11.9	0.2	1.1	ns	0.01	ns
Middle, 8-mm	32.1	29.9	25.8	21.6	1.7	0.01	0.10	ns
Bottom	58.6	69.3	62.3	78.2	2.2	0.02	0.01	ns
pef _{PS} ³ , %	41.3	30.7	37.7	21.9	2.1	0.02	0.01	ns
pef _M ⁴ , %	67.5	59.7	66.8	55.0	—	—	—	—
pef _{>1.18} ⁵ , %	73.5	63.6	68.8	59.4	1.2	0.02	0.01	ns

¹AS:AH = Ratio of alfalfa silage to alfalfa hay; CH = chopped hay; GH = ground hay; and the overall diet was 60% barley-based concentrate and 40% forage on a DM basis.

²FPS = forage particle size.

³Physical effectiveness factor determined as the proportion of dry matter retained by both sieves of the Penn State Particle Separator.

⁴Physical effectiveness factor based on chewing determined from Mertens (1997). The pef of steam-rolled barley was assumed to be 70%.

⁵Physical effectiveness factor determined as a percent of DM remaining on a 1.18-mm screen measured using a wet sieving technique.

ns = $P > 0.15$.

tion rate (milliliter per minute) by the time spent eating each day (minute) or by multiplying the ensalivation of the feed (milliliter per gram of DMI) by DMI.

Samples of ruminal contents and duodenal digesta were also obtained for particle size determination. Ruminal samples were collected by total evacuation of rumen contents, which were manually emptied at 9:30 a.m. on the last day of the period. Duodenal samples were collected during the last 3-d of the period. Samples were taken four times daily every 6 h moving ahead 2 h each day. The duodenal samples were then pooled by cow for each period.

Ruminal Fermentation

Rumen pH was measured by placing an industrial electrode (model PHCN-37; Omega Engineering, Stamford, CT) through the rumen cannulae into the ventral sac of the rumen within each cow for a 48-h period. A weight was attached to the electrode to ensure it remained in the ventral sac. A protective shield with large openings that allowed rumen fluid to percolate freely was placed around the electrode to prevent it from coming in direct contact with the ruminal epithelium. The electrodes were calibrated with pH 4.0 and 7.0 standards at 0, 24 and 48 h of the measurement period. The pH was measured every five seconds, averaged every 15 min, and recorded using a data logger. Mean ruminal pH for each cow in each period was determined by averaging the data collected during the 48 h. Hours during which pH was above 6.2 or below 5.8 were calculated assuming that the change of pH between two measuring times was linear. The area below pH 5.8 (or 6.2) and the pH curve was calculated for each cow over the entire pH measurement period. The area was calculated by adding the absolute value of the negative deviations in pH from 5.8 (or 6.2) for each 15-min interval. Values were expressed as pH units multiplied by hours. The ruminal pH 6.2 and 5.8 were chosen as benchmarks based on *in vitro* observations that ruminal microbial activity is compromised when ruminal pH drops below 6.2 (Russell and Wilson, 1996), and the incidence of sub-clinical acidosis increases when ruminal pH falls below 5.8. The lowest pH for each cow over the entire period was also recorded.

Ruminal fluid was collected on 1 d at 1000, 1300, and 1600 h from multiple sites in the rumen. Samples were immediately squeezed through four layers of cheesecloth with a mesh size of 250 μ m. Five milliliters of filtrate were preserved by adding 1 ml of 25% HPO_3 to determine VFA, and 9 ml of filtrate were preserved by adding 1 ml of 1% H_2SO_4 to determine NH_3 N.

The samples were subsequently stored frozen at -20°C until analyzed.

Feed Intake and Milk Production

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, am and pm, and sampled on five consecutive days during the last 10-d 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).

Feed DM was determined by oven-drying at 55°C for 48 h. Analytical DM content of the samples was determined by drying at 135°C for 3 h (AOAC, 1990). The OM content was calculated as the difference between DM and ash contents, with ash determined by combustion at 550°C overnight. Content of CP in the samples was determined by flash combustion (Carlo Erba Instruments, Milan, Italy). The NDF and ADF contents were determined using the methods described by Van Soest et al. (1991) with amylase and sodium sulfite used in the NDF procedure. Starch was determined by enzymatic hydrolysis of α -linked glucose polymers as described previously (Rode et al., 1999). Ruminal VFA were separated and quantified by gas chromatography (Varian 3700; Varian Specialties Ltd., Brockville, ON) using 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 plate reader.

Particle size distributions of the forages and TMR were measured using the PSPS or by wet sieving (Tables 2 and 3). The pef of forages and TMR were obtained in different ways: **pef_{PS}** was calculated as the sum of the proportions retained on the two sieves of the PSPS, and **pef_M** was calculated based on tabular values from Mertens (2000). The **pef_{P>1.18}** was determined as a percent of DM remaining on a 1.18 mm screen (diameter i.d. 20.5 cm; W. S. Tyler Inc., Mentor, OH). The peNDF was calculated by multiplying NDF content of the TMR by pef determined in each manner.

Particle size distributions of forages, TMR and digestive contents were measured by wet sieving using a

vertical oscillating sieve shaker (Analysette 3; Fritsch, Oberstein, Germany) equipped with a stack of sieves (diameter i.d. 20.5 cm; W. S. Tyler Inc.) arranged in descending pore size. Sieve pore sizes were 9.5, 6.7, 3.35, 1.18, 0.6, and 0.15 mm for forages, diets, and rumen contents, and 3.35, 1.18, 0.6, and 0.15 mm for duodenal contents. Approximately 15 g of feed or 30 g of wet digesta were placed on the top screen, and the stack of sieves were 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).

Because a wet sieving technique was used, it was necessary to account for the loss of DM due to solubilization prior to calculating mean particle length (MPL). The MPL of feeds reported are comparable to values determined by a dry sieving technique. This adjustment was made by using nonlinear optimization to fit the following modified Weibull function to the data for each sieve:

$$y = 100 (1 - e^{-b(x-x_0)^c})$$

where

- y = cumulative percentage of sample weight retained by each sieve,
- b, c = parameters of the Weibull function,
- X = total DM passing through the each sieve including small particles and solubles, and
- X₀ = the Y-intercept.

The value of X₀ represented the true soluble fraction, and it was assumed based on unpublished studies in our laboratory that the solubles were extracted from each particle size fraction in proportion to the surface area of the smallest particles in that fraction. Surface area of particles was calculated assuming particle length was 5-times particle width, width of particles was 5-times particle thickness, and all particles had a density of 1 mg/mm³. The DM retained on each sieve was adjusted by adding the calculated proportion of soluble DM to this weight. Then a second Weibull function was fitted to the adjusted cumulative DM retained on each sieve (X₀ = 0) and the parameters were estimated using NLIN procedure of SAS (SAS, 1996). The MPL was calculated as the particle length for which 50% of the cumulative percentage weight of the sample

was retained (Vaage and Shelford, 1984). The percentage of adjusted DM retained on the 1.18-mm screen was the value used for pef_{P>1.18} and thus, this estimate was similar to values obtained using a dry sieving technique as recommended by Mertens (1997).

Statistical Analyses

For each period, means for individual cows were calculated for all variables. Data were analyzed using the mixed model procedure of SAS (Proc Mixed; SAS, 1996). The model included cows, period, AS:AH, FPS, and the two-way interaction between AS:AH and FPS. Period and cow were considered random effects. For ruminal pH variables, the model also included day and the two-way interactions between treatment and day and a repeated statement was used. The Pearson correlation coefficients were estimated using the CORR procedure of SAS (SAS, 1996). Effects were declared significant at $P < 0.05$ unless otherwise noted and trends were discussed at $P < 0.15$.

RESULTS AND DISCUSSION

Particle Size Distributions of Forages and TMR

The AS used in this study with a pef_{PS} = 73.4 was considered medium to coarsely chopped compared to the industry standard. Yet, proportion of particles retained on the top sieve of the PSPS was significantly lower, and proportion of particles retained on the second sieve was threefold higher, for AS than for chopped AH (Table 2). Few particles were retained on the sieves of the PSPS for ground AH. Consequently, pef_{PS} measured as the sum of particles retained on both sieves of the PSPS was highest for the AS, lowest for the ground AH and intermediate for the chopped AH. Alfalfa silage and chopped AH had a similar proportion of particles retained on the 9.5- or 1.18-mm screens using a wet sieving technique, but a greater proportion of the forage was retained on the 6.7- and 3.35-mm screens for the AS than for the chopped AH. Grinding through a 4-mm screen removed most of the coarse particles but gave a higher proportion of particles retained on the 1.18-mm screen or smaller screens compared to the chopped AH. As a result, the MPL and pef_{P>1.18} of the forages followed the same trend as that of the pef_{PS}. However, pef was variable among the methods used. The method of Mertens (1997) gave consistently higher pef values than did the other two methods, especially for chopped AH. The pef estimated using the PSPS or the particles retained on the 1.18-mm screen was similar for AS and chopped AH but was different for ground AH.

Table 4. Intake of DM and effective fiber of dairy cows fed diets differing in ratio of alfalfa silage to alfalfa hay or forage particle size.

Item	Diets ¹				SE	Effect ² , <i>P</i> <		
	AS:AH 50:50		AS:AH 25:75			AS:AH	FPS	AS:AH × FPS
	CH	GH	CH	GH				
Intake of DM								
kg/d	23.5	23.9	20.6	20.5	2.1	0.06	ns	ns
% of BW	3.54	3.71	3.18	3.24	0.29	0.09	ns	ns
Intake of peNDF ³								
peNDF _{PS} ⁴								
kg/d	3.53	2.42	2.74	1.47	0.33	0.01	0.01	ns
% of DMI	15.0	10.1	13.3	7.2	0.8	0.02	0.01	ns
peNDF _M ⁵								
kg/d	5.78	4.68	4.87	3.75	0.52	0.03	0.01	ns
% of DMI	24.5	19.6	23.6	18.3	0.4	0.02	0.01	ns
peNDF _{P>1.18} ⁶								
kg/d	6.29	4.98	4.99	4.06	0.53	0.01	0.01	ns
% of DMI	26.7	20.9	24.3	19.7	0.3	0.01	0.01	0.01
BW, kg	663	646	648	634	5.4	0.06	0.03	ns

¹AS:AH = Ratio of alfalfa silage to alfalfa hay; CH = chopped hay; GH = ground hay; and the overall diet was 60% barley-based concentrate and 40% forage on a DM basis.

²FPS = forage particle size.

³Physically effective NDF.

⁴Physically effective NDF measured as the NDF intake multiplied by pef_{PS} (Table 3).

⁵Physically effective NDF measured as the NDF intake multiplied by pef_{M} (Table 3).

⁶Physically effective NDF measured as the NDF intake multiplied by $\text{pef}_{P>1.18}$ (Table 3).

ns = *P* > 0.15.

The TMR used in this study containing AS and chopped AH was considered of sufficient particle size to maintain healthy rumen function, whereas the diets containing AS and ground AH were designed to supply less than adequate particle size. Consequently, for the TMR, the fraction of particles retained on the top screen of the PSPS was not affected by the AS:AH but was reduced by replacing chopped AH with ground AH (Table 3). However, the fraction of the particles retained on the second screen of the PSPS was more affected by the AS:AH than the FPS because pef_{PS} was significantly different for the AS and the AH. The pef of the diets was affected both by the AS:AH and the FPS regardless of the method used to determine FPS. However, the pef_{PS} was only about 50% of the pef_{M} or $\text{pef}_{P>1.18}$ since the pef_{PS} did not include steam-rolled barley while the pef_{M} or $\text{pef}_{P>1.18}$ did. In fact, over 80% of the rolled barley kernels are retained by a 3.35 mm screen (Yang et al., 2000).

Intakes of DM and peNDF

Intake of DM, expressed as kilograms per day or as percentage of BW, did not differ for cows fed diets containing chopped hay or ground hay but tended (*P* < 0.10) to differ with a change of the ratio of AS:AH (Table 4). Lack of effect of FPS on DMI was consistent

with the results of Rode et al. (1985) and Soita et al. (2000) but was opposite to others (Jaster and Murphy, 1983; Rode and Satter, 1988). Influence of FPS on DMI may depend upon forage level in the diets of dairy cows. Belyea et al. (1985) reported that decreased FPS increased intake of cows fed only forage, but FPS had no effect on intake of cows fed forage plus concentrate because ruminal fill was not a limiting factor for DMI. In addition, DMI was affected by long forage but not by chopped or ground forage in diets of dairy cows (Rode et al., 1985). Effect of alfalfa preservation (silage vs. hay) on DMI is inconsistent in the literature. Nelson and Satter (1992) reported that cows fed AS-based diets consumed 1.2 kg more DM than those fed AH-based diets, while others (Broderick, 1995; Beauchemin et al., 1997) found that DMI was higher for cows fed AH than for cows fed AS.

Intake of peNDF followed the same trend as pef contents of the diets and was affected by both FPS and AS:AH. Cows fed the diets containing chopped AH or high AS:AH had greater intake of peNDF than did cows fed the diets containing ground AH or low AS:AH because pef was higher for AS than for AH and peNDF of the diets was estimated based on particle size of the diets. In addition, proportion of peNDF_M and peNDF_{P>1.18} in the diets (DM basis) varied from 18.3 to 26.7% of DM which was in the range of the minimum recom-

Table 5. Chewing activity and salivary production during eating of dairy cows fed diets differing in ratio of alfalfa silage to alfalfa hay or forage particle size.

Item	Diets ¹				SE	Effect ² , <i>P</i> <		
	AS:AH 50:50		AS:AH 25:75			AS:AH	FPS	AS:AH × FPS
	CH	GH	CH	GH				
Chewing activity								
Eating activity								
h/d	4.8	4.2	4.7	5.3	0.3	ns	ns	0.09
Min/kg DM	12.5	10.8	14.8	15.5	1.7	0.01	ns	ns
Min/kg NDF	34.5	32.9	42.2	46.6	5.2	0.02	ns	ns
Ruminating time								
h/d	7.3	6.2	7.0	4.6	0.6	0.04	0.01	0.08
Min/kg DM	19.1	15.7	20.8	13.5	1.6	ns	0.01	0.07
Min/kg NDF	52.7	48.1	59.1	40.5	5.1	ns	0.01	0.07
Total chewing time								
h/d	12.1	10.4	11.7	9.9	0.8	ns	0.02	ns
Min/kg DM	31.6	26.5	35.6	28.9	2.7	0.07	0.01	ns
Min/kg NDF	87.1	81.0	101.3	87.1	8.6	0.11	0.11	ns
Salivary secretion								
Salivation rate ³ , ml/min	198.9	191.1	173.9	219.6	15.2	ns	ns	0.08
Ensalivation ⁴ , ml/g DM	3.7	2.6	2.7	3.7	0.3	ns	ns	0.05
Output during eating, L/d								
Salivation rate × eating time	58.9	50.8	48.5	68.7	5.8	ns	ns	0.02
Ensalivation × DMI	81.8	59.7	55.5	75.9	7.9	ns	ns	0.02

¹AS:AH = Ratio of alfalfa silage to alfalfa hay; CH = chopped hay; GH = ground hay; and the overall diet was 60% barley-based concentrate and 40% forage on a DM basis.

²FPS = forage particle size.

³Ratio of total amount of saliva secreted to duration of collection for each individual collection.

⁴Amount of saliva added per gram of feed ingested.

ns = *P* > 0.15.

mendation. Mertens (2000) recommended that 19.7% peNDF was needed to maintain a milk fat percentage of 3.4% for Holstein cows, and 22.3% peNDF was needed to maintain an average ruminal pH of 6.0. However, the proportion of peNDF_{PS} ranged only from 7.2 to 15% of the diet DM. Furthermore, it is apparent that peNDF did not influence feed intake. Although pef contents of the diets within the same ratio of AS:AH were different, the DMI were similar.

Chewing Activity, Salivary Secretion, and Particle Size Distribution

Total eating time (hours per day) was not affected by treatments (Table 5). However, cows spent a longer time eating per unit of feed intake (DM or NDF) when fed low AS:AH than high AS:AH diets. Increasing the proportion of hay in the diet of cows required more time for eating but total eating time was not increased because intake decreased. This effect was not likely due to the FPS, as cows spent similar time eating per unit of feed for diets containing chopped or ground AH. Lack of an effect of the FPS on eating time suggests that even the chopped AH was below the critical particle size required prior to swallowing.

Cows spent less time ruminating with decreased ratio of AS:AH in the diet or with reduced FPS. Higher ruminating time for the diet with high AS:AH ratio compared to the diet with low AS:AH ratio reflected higher DMI rather than a direct effect due to alfalfa preservation because this difference was not evident when ruminating time was expressed per unit of feed intake. In contrast, ruminating time, expressed as minute per unit of intake of DM or NDF, decreased with reduction of the FPS. Similarly, total chewing time was not affected by AS:AH but it was lower for the diet containing ground hay than for the diet containing chopped hay. This finding was in agreement with other reports (Nelson and Satter, 1992; Beauchemin et al., 1997), and indicates that differences between the potential rumination of AS or AH are related primarily to particle size rather than method of preservation per se. Beauchemin et al. (1994) reported that the particle size of silage did not affect the eating time but reduced ruminating time.

There were interactions (*P* < 0.08) observed between AS:AH and FPS for ruminating time. Replacing chopped hay with ground hay had a more pronounced effect on ruminating time for low AS:AH than for high AS:AH diets. This effect was likely associated with

Table 6. Particle size distribution and particle length of diets and digesta of dairy cows fed diets differing in ratio of alfalfa silage to alfalfa hay or forage particle size.

Item	Diets ¹				SE	Effect ² , <i>P</i> <		
	AS:AH 50:50		AS:AH 25:75			AS:AH	FPS	AS:AH × FPS
	CH	GH	CH	GH				
MPL ³ , mm								
Diets	9.78	5.13	7.45	4.42	0.56	0.06	0.01	ns
Masticate	4.33	3.69	4.47	3.55	0.43	ns	0.12	ns
Rumen	3.65	3.29	3.44	3.19	0.16	ns	0.07	ns
Duodenum	2.88	3.05	2.77	2.22	0.41	ns	0.13	ns
DM retained on sieve, %								
Diets								
6.70 mm	24.8	5.5	16.3	3.2	1.9	0.05	0.01	ns
3.35 mm	33.0	36.6	34.1	30.4	1.9	ns	ns	ns
1.18 mm	14.2	20.9	16.7	24.3	0.9	0.04	0.01	ns
<1.18 mm	11.1	17.8	14.2	20.4	0.5	0.02	0.01	ns
Not retained	16.9	19.2	18.7	21.7	1.1	0.14	0.08	ns
Masticate								
6.70 mm	8.2	3.5	8.0	2.4	0.9	ns	0.01	ns
3.35 mm	21.7	27.0	25.8	25.6	2.7	ns	0.1	0.07
1.18 mm	21.1	21.8	21.5	21.8	1.4	ns	ns	ns
<1.18 mm	14.6	16.0	15.5	18.0	0.7	0.03	0.01	ns
Not retained	34.4	31.7	29.2	32.2	4.0	ns	ns	ns
Rumen								
6.70 mm	4.6	1.0	4.6	0.8	0.6	ns	0.01	ns
3.35 mm	13.6	11.7	12.9	12.0	1.6	ns	ns	ns
1.18 mm	29.8	34.8	28.5	32.6	2.0	0.07	0.01	ns
<1.18 mm	29.2	26.7	28.6	26.3	2.1	ns	ns	ns
Not retained	22.8	25.8	25.4	28.3	1.5	0.09	0.05	ns
Duodenum								
3.35 mm	4.2	3.6	3.4	2.6	0.3	0.01	0.01	ns
1.18 mm	41.8	42.7	40.0	31.9	2.5	0.02	ns	0.09
<1.18 mm	18.5	20.1	17.1	19.0	1.4	0.07	0.02	ns
Not retained	35.5	33.6	39.5	46.5	3.3	0.01	ns	0.12

¹AS:AH = Ratio of alfalfa silage to alfalfa hay; CH = chopped hay; GH = ground hay; and the overall diet was 60% barley-based concentrate and 40% forage on a DM basis.

²FPS = forage particle size.

³Fifty percent of the particles are greater or less than this length.

ns = *P* > 0.15.

intake (kilogram per day) of peNDF rather than the MPL of the diet (Table 6) because the decreased intake of peNDF_{PS} due to replacing chopped hay with ground hay was more pronounced for low AS:AH (42%) than for high AS:AH (25%) diets. In contrast, the reduction of diet MPL was less for low (41%) than for high (48%) AS:AH diets.

Total chewing time varied from 9.9 to 12.1 h with ruminating time varying from 4.7 to 7.3 h, which are in the ranges reported previously for dairy cows fed diets containing barley grain and alfalfa (Beauchemin et al., 1994; Yang et al., 2000). High producing dairy cows consuming large quantities of DM tended to ruminate more than 6 h daily, unless a digestive upset occurs (Beauchemin et al., 1994). This is equivalent to a minimum of 16 min/kg of DM for 22 kg/d of DMI. In the present study, the shortest rumination time was only 4.6 h/d or 13.5 min/kg of DMI for cows fed the diet containing low AS:AH and ground hay with

the lowest intake of peNDF among the four diets studied. Sudweeks et al. (1981) proposed chewing corrected for DMI as a criterion for physical effectiveness of forages. They further proposed values equal or more than 30 min/kg of DMI as suitable for limiting the risk of digestive disorders. In the present study, cows fed the diets containing ground hay either with high or with low AS:AH chewed less 30 min/kg of DMI when intake of peNDF_M was below 20% but cows chewed more than 30 min/kg of DMI when the intake of peNDF_M was over 23%, indicating that the peNDF, expressed as percentage of DMI, might be a reliable indicator of chewing activity. However, the values of peNDF (% of DMI) can be much lower when the PSPS technique is applied compared with the peNDF_M or peNDF_{P > 1.18}. Guidelines for dietary levels of peNDF based on chewing time need to be developed.

The rate of saliva secretion during eating was not affected by the treatments and was in the range re-

ported by Beauchemin (2000) for dairy cows (Table 5). This observation supports the previous work that indicates that salivary secretion per minute of mastication is relatively constant, and is not usually affected by diet (Cassida and Stokes, 1986). Similarly, ensalivation of feed, expressed as gram of saliva added per gram of feed swallowed, and as well as total salivary output during the eating period were not affected by the treatments regardless the methods used for estimating salivary output. However, total salivary production during eating was consistently higher when DMI rather than eating time was used in the calculation. This discrepancy indicates that eating time (hours per day) might not be properly estimated by visual observation because DMI and salivation rate were directly measured. Furthermore, there were interactions observed between AS:AH and FPS for salivation rates, ensalivation of feed and saliva production during the eating period. Decreasing peNDF level of the diet by replacing chopped AH with ground AH increased saliva secretion in low AS:AH diets but not with high AS:AH diets. It is possible that the addition of ground hay compared with chopped hay increased saliva production more in low silage diets because the ground hay has more potential to absorb free moisture. The quality of the bolus in terms of lubrication and ease of swallowing may be more a function of free moisture than total moisture content. Thus, a smaller amount of saliva is able to lubricate a coarse forage than a fine forage.

Mean particle length and particle size distributions of the diets, masticates and digestive contents are presented in Table 6. The FPS tended to affect MPL of the diet, the masticate ($P < 0.12$), rumen contents ($P < 0.07$) and duodenal digesta ($P < 0.13$). Although lowering the ratio of AS:AH tended to reduce ($P < 0.06$) the MPL of the diets because the MPL was greater for AS than for AH, it had no effect on MPL of masticate, rumen contents, or duodenal digesta. Furthermore, despite the fact that the MPL declined linearly from the diet to the duodenal digesta for all diets, the reduction of the MPL was greater from diet to masticate than from the masticate to rumen contents or from rumen contents to duodenal digesta, especially for the diets containing chopped hay. In fact, comparing particle distributions between diet and masticate indicates that eating reduced substantially the proportion of particles retained on the 6.7 or 3.35-mm screens with minimal changes in proportions of particles retained or passing through a 1.18-mm screen. The sum of the proportion of the particles retained on the 6.7, 3.35 and 1.18-mm screens varied from 58 to 72% of the total DM among the diets studied but that of the masticate was relatively consistent and varied from 50 to

55%. These data indicate that eating activity was more efficient for long particles than for short ones. This finding is in agreement with that of Bailey et al. (1989) who reported that larger feed particles were reduced more in size than smaller ones during eating.

As observed for the MPL, AS:AH had almost no affect on particle distributions of the masticate while the proportion of the particles retained on a 6.7-mm screen was higher for the diet containing chopped hay than for the diet containing ground hay. Consequently, more rumination was needed for the diet containing chopped hay (Table 5).

Influences of the treatments on particle size distributions of rumen contents were quantitatively negligible despite some differences that were statistically significant (Table 6). In the duodenum, no particles were retained on a 6.7-mm screen and the proportion of the particles retained on a 3.35-mm screen was reduced, on average, from 15% in the rumen contents to 3.5% in the duodenal digesta while proportion of particles retained on the 1.18-mm screen was increased up to 43%. These data indicate that particles retained on a 1.18-mm screen may not have a high resistance to passage from the rumen to the duodenum in cattle and suggest that the peNDF should be estimated from particles retained on the 3.35 or 2.36-mm screens rather than the 1.18-mm screen.

Rumen Fermentation

The pattern of diurnal fluctuation of ruminal pH was generally similar among the treatments (Figure 1). The highest pH values were observed just before the 8-am feeding, while the lowest pH values were between 2000 and 0200 h. Cows fed the diets with low AS:AH or the diets containing chopped hay had ruminal pH values consistently higher than the cows fed the diets with high AS:AH or the diets containing ground hay. In addition, the pH curves were relatively flat for the diets with low AS:AH or the diet containing chopped hay. Consequently, mean ruminal pH tended to be higher ($P < 0.10$) for low AS:AH than for high AS:AH diets, and lower for the diet containing ground hay than for the diet containing chopped hay (Table 7). These results are in agreement with the recommendation (22.3% peNDF) of Mertens (1997) when peNDF content of the diet is measured from tabular values (Mertens, 2000) or from the particles retained by a 1.18-mm screen. Furthermore, ruminal pH was mainly affected by FPS rather than AS:AH. In fact, decreased ratio of AS:AH tended to prolong ($P < 0.08$) the period in which pH was above 6.2. Feeding chopped hay instead of ground hay improved significantly ruminal pH status: the period in which ruminal pH was

Figure 1. Diurnal fluctuations of rumen pH affected by ratio of alfalfa silage to alfalfa hay (a; silage:hay, 50:50, —; 25:75, ---) or by particle size of hay (b; chopped, —; ground, ---). Arrows indicate time of feeding.

above 6.2 tended to increase ($P < 0.11$) and the period during which ruminal pH was below 5.8 decreased.

Improved ruminal pH by manipulating the FPS of diets was likely due to increased rumination time. Higher DMI combined with lower eating time (minutes per kilogram of DMI) was probably the major cause for lower ruminal pH with high AS:AH diets. Lower ruminal pH was consistent with less time spent chewing for diets containing ground hay compared with the diets containing chopped hay. Furthermore, more rapid solubilization of non-cell wall components from the ground hay was possibly an additional factor leading to low ruminal pH.

Effects of AS:AH and FPS on ruminal pH were not consistent with the effects on ruminal VFA content or molar percentage of acetate, propionate or butyrate, which were not affected by the dietary factors studied in the present experiment. The present findings conflict with other results (Nelson and Satter, 1992) in which both the ruminal pH and VFA concentrations were affected by the particle size of alfalfa. A relatively short sampling period (one day from 1000 to 1600 h) for ruminal VFA determination was not as representative as the continuous measurement of ruminal pH during two days. Ruminal NH_3 N concentration was similar for diets containing chopped or ground hay but was increased when the AS:AH was reduced. This finding was in contrast to what was expected because AS contained more RDP than did AH.

Production and Composition of Milk

Milk production tended to be increased by 11.2% for actual ($P < 0.14$), and 9.8% for FCM ($P < 0.09$) when AS:AH in the diets of cows was increased from 25:75 to 50:50 (Table 8). However, there were no differences in milk production for cows fed chopped hay or ground hay, reflecting similar trends for DMI. Milk composition was not affected by the AS:AH or FPS. Consequently, milk component yield did not differ for cows fed chopped or ground hay but yield of milk fat tended to be higher ($P < 0.07$) for cows fed high AS:AH than for cows fed low AS:AH diets, because of greater actual milk yield. Trends toward increased milk production by feeding high AS:AH were a result of trends towards increased DMI. Several factors may explain lack of response of milk fat to peNDF content of the diet. Firstly, the NDF contents of the diets in the present study were higher (36%) than the minimum (25%) recommendation of NRC (2001), although the proportion of forage NDF in the diets was the recommended level of 19%. Beauchemin et al. (1994) and Mertens (1997) concluded that effects of particle size on milk fat content were likely to be observed when NDF levels were below minimum requirements recommended by NRC (1989). Secondly, the lowest peNDF of the diet (19.7%) measured as the particles retained on a 1.18-mm screen, was equal to the recommendation of Mertens (1997) to maintain milk fat at 3.4% for early to midlactation Holstein cows.

Correlations of peNDF with Chewing Activity or Rumen pH

Pearson correlation coefficients among the 16 observations for each variable are presented in Table 9. Dietary particle sizes, expressed as MPL, peNDF_M or

Table 7. Characteristics of rumen fermentation of dairy cows fed diets differing in ratio of alfalfa silage to alfalfa hay or forage particle size.

Item	Diets ¹				SE	Effect ² , <i>P</i> <		
	AS:AH 50:50		AS:AH 25:75			AS:AH	FPS	AS:AH × FPS
	CH	GH	CH	GH				
pH								
Mean	5.97	5.78	6.18	5.90	0.15	0.10	0.02	ns
Area pH < 5.8, pH* <i>h</i>	2.1	3.7	0.9	4.5	1.1	ns	0.01	ns
Area pH < 6.2, pH* <i>h</i>	6.9	10.5	4.4	10.2	2.2	ns	0.01	ns
> 6.20, <i>h</i>	7.3	3.5	11.0	7.6	3.3	0.08	0.11	ns
< 5.80, <i>h</i>	7.5	13.0	5.1	11.7	2.6	ns	0.01	ns
Lowest	5.40	5.26	5.66	5.42	0.14	0.07	0.09	ns
VFA								
Total, mM	143.4	145.7	133.3	133.7	10.8	ns	ns	ns
mol/100 mol								
Acetate (A)	64.4	65.6	67.9	66.0	1.5	ns	ns	ns
Propionate (P)	20.1	18.1	17.5	18.8	2.0	ns	ns	ns
Butyrate	11.7	11.7	10.6	11.3	0.8	ns	ns	ns
A:P	3.41	3.72	3.95	3.77	0.45	ns	ns	ns
NH ₃ N, mM	3.23	3.55	4.80	4.05	0.48	0.01	ns	0.13

¹AS:AH = Ratio of alfalfa silage to alfalfa hay; CH = chopped hay; GH = ground hay; and the overall diet was 60% barley-based concentrate and 40% forage on a DM basis.

²FPS = forage particle size.

ns = *P* > 0.15.

peNDF_{P>1.18} were moderately correlated with ruminating or total chewing time ($r \geq 0.52$, $P < 0.05$) but not with eating time, and the peNDF_{PS} only tended to correlate to ruminating time ($r = 0.44$, $P < 0.10$). Lack of correlation between peNDF and eating time indicated that no effect of peNDF on eating time was observed. Low correlation of intake of peNDF_{PS} with chewing activity was not expected because the

peNDF_{PS} represents the portion of the coarse particles of the diets which supposedly stimulate chewing activity. However, there were considerable differences in the proportion of coarse particles of the diets measured using the PSPS or the wet sieving technique. The proportion of particles retained on the 8 mm sieve of the PSPS was 31.5, 30.7, 37.7, and 21.8% while that retained on the 6.7 mm screen used in wet sieving was

Table 8. Milk production and composition of dairy cows fed diets differing in ratio of alfalfa silage to alfalfa hay or forage particle size.

Item	Diets ¹				SE	Effect ² , <i>P</i> <		
	AS:AH 50:50		AS:AH 25:75			AS:AH	FPS	AS:AH × FPS
	CH	GH	CH	GH				
Milk yield, kg/d								
Actual	29.4	29.2	26.2	26.5	2.9	0.14	ns	ns
4% FCM	28.3	27.9	25.3	25.9	2.1	0.09	ns	ns
Milk fat								
%	3.92	3.78	3.80	3.93	0.44	ns	ns	ns
kg/d	1.10	1.08	0.98	1.02	0.09	0.07	ns	ns
Milk protein								
%	3.26	3.34	3.31	3.31	0.16	ns	ns	ns
kg/d	0.95	0.96	0.87	0.87	0.10	ns	ns	ns
Milk lactose								
%	4.62	4.63	4.57	4.60	0.07	ns	ns	ns
kg/d	1.36	1.35	1.20	1.22	0.13	ns	ns	ns
4% FCM/DMI	1.22	1.19	1.27	1.27	0.10	ns	ns	ns

¹AS:AH = Ratio of alfalfa silage to alfalfa hay; CH = chopped hay; GH = ground hay; and the overall diet was 60% barley-based concentrate and 40% forage on a DM basis.

²FPS = forage particle size.

ns = *P* > 0.15.

Table 9. Pearson correlation coefficients¹ for parameter measurements among 16 observations.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Intake of NDF, kg/d	0.32															
2. MPL, mm	0.29	0.88														
3. Intake of peNDF _{PS} , ³ % of DM	0.37	0.95	0.91													
4. Intake of peNDF _M , ⁴ % of DM	0.34	0.98	0.98	0.98												
5. Intake of peNDF _{P>1.18} , ⁵ % of DM	0.03	-0.02	-0.24	-0.10	-0.01											
6. Eating time, min/d	0.54	0.57	0.44	0.60	0.58	-0.06										
7. Ruminating time, min/d	0.52	0.31	0.52	0.54	0.54	0.36	0.91									
8. Total chewing time, min/d	-0.10	-0.16	-0.46	-0.30	-0.18	0.69	-0.04	0.25								
9. Eating salivary output, L/d	0.01	0.01	0.18	-0.02	-0.02	-0.02	-0.24	-0.25	-0.45							
10. Ruminal mean pH	0.40	-0.37	-0.51	-0.40	-0.35	0.31	0.19	0.30	0.47	-0.36						
11. pH < 5.8, h	0.32	-0.39	-0.55	-0.48	-0.43	0.39	0.05	0.21	0.53	-0.24	0.94					
12. Area pH < 5.8 (pH·h/d)	0.50	0.06	0.15	0.46	0.44	0.04	0.46	0.44	0.36	-0.24	0.59	0.48				
13. Ruminal VFA, mM	-0.68	-0.12	-0.34	-0.61	-0.56	-0.22	-0.35	-0.41	-0.39	0.22	-0.72	-0.71	-0.65			
14. Acetate, % of total VFA	0.62	0.13	0.39	0.57	0.53	0.33	0.26	0.38	0.36	-0.11	0.55	0.56	0.50	-0.89		
15. Propionate, % of total VFA	0.70	0.10	-0.12	0.03	0.05	0.19	0.55	0.59	0.33	-0.32	0.69	0.61	0.66	-0.65	0.48	
16. Milk production, kg/d	-0.31	0.02	0.18	0.01	-0.02	-0.31	-0.21	-0.32	-0.29	0.53	-0.38	-0.31	-0.31	0.24	-0.32	-0.59
17. Milk fat content, %																

¹Correlation coefficients were significant at $P < 0.01$ (> 0.62 or < -0.62), $P < 0.05$ (> 0.50 or < -0.50), and $P < 0.15$ (> 0.38 or < -0.38).²Fifty percent of the particles are greater or less than this length.³Physically effective NDF measured as the NDF content of the TMR multiplied by pef_{PS} (Table 3).⁴Physically effective NDF measured as the NDF content of the TMR multiplied by pef_M (Table 3).⁵Physically effective NDF measured as the NDF content of the TMR multiplied by pef_{P>1.18} (Table 3).

24.8, 5.5, 16.3, 3.2% for the four diets studied, respectively. Apparently, compared with wet sieving, the PSPS overestimated the proportion of coarse particles, especially for the diets containing a high proportion of fine particles.

The MPL or peNDF of the diets were not correlated to mean ruminal pH but were negatively correlated to the area below pH 5.8 and the time during which ruminal pH was below 5.8. Reducing this area indicated an increase of ruminal pH and a reduction of ruminal pH fluctuations. The negative correlation between peNDF of the diets and the area below pH 5.8 was likely related to rumination time rather than eating time. Rumen pH below 5.8 mostly occurred during night-time rather than during day-time (Figure 1). Hence, increasing ruminating time rather than increasing eating time may be a more efficient means of improving ruminal pH status. Increased ruminating time could be achieved by manipulating the peNDF content of diet as it was positively correlated to ruminating time. These results suggest that increased peNDF content of the diet may not affect mean ruminal pH but may reduce the risk of acidosis by decreasing the time and area that pH is below 5.8. A positive correlation between ruminal pH and milk fat content ($r = 0.53$, $P < 0.05$) was expected as high ruminal pH promotes fiber digestion which produces precursors for milk and milk fat synthesis.

CONCLUSIONS

Estimates of physically effective NDF content of diets differed for the various techniques used. The physically effective NDF content of the diets was much lower when measured using the Penn State Particle Separator than when measured based on particles retained on a 1.18-mm screen or from tabular values of chewing times. Increasing physically effective NDF content of dairy cow diets increased chewing activity, especially ruminating time, and improved rumen pH status. The peNDF was a reliable indication of chewing activity and subclinical ruminal acidosis (time and area below pH 5.8), but not mean ruminal pH. Furthermore, chewing activity was related more to peNDF_M and peNDF_{P>1.18} than peNDF_{PS}. About 22% of DMI as peNDF is needed in dairy cow diets to maintain an average ruminal pH of 6.0 when using particles retained on a 1.18-mm screen to determine the peNDF level. Further study is warranted to validate these different systems for optimizing level of the peNDF in the dairy cow diet.

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