Effects of the Chop Lengths of Alfalfa Silage and Oat Silage on Feed Intake, Milk Production, Feeding Behavior, and Rumen Fermentation of Dairy Cows

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ABSTRACT

Effects of chop length (shorter: 6 mm, or longer: 19 mm) of alfalfa silage and oat silage were determined in 16 mid-lactation Holstein cows, 4 of which were rumen cannulated, using a replicated 4 × 4 Latin square design with a 2 × 2 arrangement of treatments. Experimental periods were 21 d long and consisted of 14 d of adaptation and 7 d of sampling. Cows received a total mixed ration containing [dry matter (DM) basis] 42.0% barley grain-based energy supplement, 10% protein supplement, and 24% of DM longer chop or shorter chop alfalfa silage and 24% of DM longer chop or shorter chop oat silage. Rumen pH was measured continuously, and rumen liquid flow rates were determined in rumen-cannulated cows. Feeding behavior was determined by videotaping, and meal patterns were determined by continuously weighing the feed in the bunk of 8 cows. Reducing the chop length of alfalfa silage and oat silage reduced the average geometric particle length from 14.2 to 10.9 mm and from 13.4 to 10.4 mm, respectively. Reducing the alfalfa chop length did not affect feed intake, whereas reducing the oat silage chop length increased DM intake from 19.4 to 21.2 kg/d. Reducing the chop lengths of alfalfa silage and oat silage chop length did not affect milk production, rumen fermentation, feeding behavior, meal patterns, and blood metabolites. Daily milk yield, milk fat percentage, and milk protein percentage averaged 36.1 kg/d, 3.00%, and 3.16%, respectively, across diets. The low milk fat percentages suggest that the diets induced subacute ruminal acidosis. This was also substantiated by the rumen pH, which was below 5.6 for more than 122 min/d for all diets. The onset of subacute ruminal acidosis despite apparently adequate dietary neutral detergent fiber content and particle size distribution as well as the long duration of chewing might be attributed to sorting against long feed particles.

Key words: forage chop length, feeding behavior, dairy cow, rumen pH

INTRODUCTION

A recent survey demonstrated wide ranges in particle size distributions and particle lengths of legume silages and grain crop silages used on Manitoba dairy farms (Plaizier et al., 2004). Thirty-five percent of alfalfa silage samples and 30% of the corn silages samples collected in this survey conformed to the recommendations by Heinrichs and Kononoff (2002). Conversely, 35% of alfalfa silage samples and 30% of corn silage samples had particle lengths that were shorter than these recommendations (Plaizier et al., 2004).

Silage particle lengths can affect the production and health of dairy cows, as long silage particle length can result in poor silage fermentation (Johnson et al., 2003), and shorter silage particle length can increase the risk of subacute ruminal acidosis (SARA; Mertens, 1997; Stone, 2004). Although considerable research has been conducted to explore the impact of feed particle length on rumen function and milk production, the results have been inconclusive. Several studies have shown that reducing the particle length of alfalfa silage, barley silage, and corn silage does not affect rumen pH (Kononoff and Heinrichs, 2003b; Yang and Beauchemin, 2006a), whereas others have demonstrated a reduction in rumen pH (Krause et al., 2002b; Beauchemin et al., 2003). Studies have also shown that reducing the forage particle length can increase DMI (Kononoff and Heinrichs, 2003a; Yang and Beauchemin, 2006a), have no effect on DMI (Beauchemin et al., 2003; Kononoff and Heinrichs, 2003b), or reduce DMI (Krause and Combs, 2003). Reducing the particle lengths of alfalfa silage and corn silage can lower milk fat (Kononoff and Heinrichs, 2003b; Krause and Combs, 2003). However, other studies did not observe this effect (Krause et al., 2002a; Beauchemin et al., 2003; Kononoff and Heinrichs, 2003a). The disparities among studies may be caused by interactions between numerous factors, including reduced forage particle size, grain source, forage source,

Received May 10, 2007.

Accepted February 2, 2008.

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forage to concentration ratio, range of particle lengths, and forage NDF content. Also, in most earlier studies, silage particle size was not altered by changing the chop length at harvesting, but by rechopping after ensiling. Hence, the effects of reducing silage chop length are difficult to predict from the results obtained in these studies. Many studies have been conducted on the effects of the particle lengths of alfalfa silage, corn silage, and barley silage (Krause and Combs, 2003; Yang and Beauchemin, 2006a,b; Bhandari et al., 2007), but very little information is available on the effects of the particle length of oat silage.

Bhandari et al. (2007) observed that reducing the chop length of alfalfa silage and corn silage from 19 to 10 mm and incorporating these silages in a barley grain-based TMR did not affect milk production. These authors also found that these reductions in chop length did not affect rumen pH, but this finding was constrained by infrequent sampling of rumen fluid. The objectives of our study were to determine the effects of chop lengths of alfalfa silage and oat silage on feed intake, feeding, chewing behaviors, rumen fermentation, milk production, and blood parameters in lactating dairy cows fed an alfalfa silage, oat silage, and barley grain-based TMR.

MATERIALS AND METHODS

Experimental Procedures

Sixteen multiparous lactating Holstein cows, housed in a tie-stall barn at the Glenlea Research Station, University of Manitoba, were used in a replicated 4 × 4 Latin square design with a 2 × 2 arrangement of treatments. The experimental design was balanced for the residual effects. Feeding behavior and water intake were determined for the rumen-cannulated cows, which composed one square, as well as for the cows of another square. Each experimental period consisted of a 14-d adaptation period, followed by a 7-d collection period. Animals were cared for in accordance with the Canadian Council for Animal Care guidelines (CCAC, 1993). Upon commencement of the experiment, cows were on average 64.9 ± 25.9 d in milk (mean ± SD), with an average BCS of 3.09 ± 0.25 on a 5-point scale (Edmonson et al., 1989) and an average BW of 611 ± 78 kg.

Second-cut alfalfa (Pickseed Custom Forage Mix, Pickseed Canada Inc., Winnipeg, MB, Canada) was harvested in the late bud stage. Oats (Ronald, SeCan, Kanata, ON, Canada) were harvested in the milk stage. Oats and alfalfa that were grown on the same field were chopped to either 6 mm (shorter chop) or 19 mm (longer chop) using a New Holland Forage Harvester, model 790 (New Holland Inc., New Holland, PA). Both the 19-mm and 6-mm chop lengths were harvested on the same

day for each crop. Alfalfa silage and oat silage were ensiled and stored in plastic-covered piles of approximately 30 tons without additives or inoculants for 3 mo and 1 mo before the beginning of the experiment, respectively.

Cows were assigned to 1 of 4 diets during each of the 4 experimental periods (Table 1). Diets were fed as TMR and contained (DM basis) 42.0% barley grain-based energy supplement (containing 42% pellets) and 10.0% protein supplement (containing 58% pellets; Table 1 and 2), 24% of either longer or shorter chop of alfalfa and 24% of either longer or shorter chop of oat silage. The concentrate to forage ratio was 52:48 on a DM basis. Diets were mixed using a Data Ranger mixer (American Calan, Northwood, NH) with a Weigh Tronix weigh head (model 1000, American Calan). The TMR were fed once daily for ad libitum consumption allowing 5 to 10%orts. Cows had unlimited access to water.

DMI and Feed Analyses

During the collection periods, the amounts of TMR offered and refused were recorded daily for each cow. Diet samples and individual ort samples were collected daily. Diet samples were collected daily and pooled for each collection period. Individual cow ort samples were obtained daily during the collection periods and pooled by period by mixing equal proportions of the daily orts. Forages samples were collected once per collection period. The DM content of pooled diet samples, pooled orts samples, and forage samples were determined by drying at 60°C for 48 h. Dried feed samples were ground using a Wiley mill through a 1-mm screen (Thomas-Wiley, Philadelphia, PA) and stored at -20°C until analyzed. Before subsequent analysis, analytical DM was determined (method 934.01; AOAC, 1990). All feed samples were analyzed for CP using the CuSO₄/TiO₂ mixed catalyst Kjeldahl procedure (method 988.05; AOAC, 1990), for NDF using α -amylase (Van Soest et al., 1991; A3306, Sigma Chemical Co., St. Louis, MO), for sodium sulfite and corrected for ash concentration adapted for Ankom 200 Fiber Analyzer (Ankom Technology, Fairport, NY), for ADF (method 973.18; AOAC, 1990), for ether extract (method 920.39; AOAC, 1990), and for ash (method 942.05; AOAC, 1990). Calcium, P, K, Mg, and Na were measured by inductively coupled plasma emission spectrometry (method 968.08; AOAC, 1990) using an Atom Scan 25 plasma spectrometer (Thermo Jarrell Ash Corp., Grand Junction, CO) after acid digestion.

Particle size distributions were determined for all TMR, pooled refusals per animal per period, and forage samples using the Penn State Particle Separator (PSPS; Kononoff et al., 2003). Approximately 150 g of wet sample was placed on the top screen of the PSPS.

Table 1. Ingredients and nutrient composition of experimental diets containing shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Diet ingredients, % of DM	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Shorter chop alfalfa silage	—	—	24	24				
Longer chop alfalfa silage	24	24	—	—				
Shorter chop oat silage	—	24	—	24				
Longer chop oat silage	24	—	24	—				
Energy supplement	42	42	42	42				
Protein supplement	10	10	10	10				
Nutrient composition ²								
DM, %	46.3	48.1	46.9	49.8	0.46	0.09	<0.05	0.44
CP, % of DM	15.8	15.4	15.5	16.7	0.17	0.06	0.09	0.21
ADIP, ³ % of DM	1.4	2.3	2.3	2.4	0.27	0.23	0.38	0.38
NDF, % of DM	38.7	38.3	38.5	37.9	0.93	0.57	0.71	0.90
ADF, % of DM	27.2	30.3	28.1	26.1	0.74	0.13	0.60	0.09
Ether extract, % of DM	3.0	3.6	3.4	3.7	0.20	0.74	0.51	0.54
Ash, % of DM	10.7	10.2	10.5	11.5	0.32	0.85	0.91	0.84
NFC, ⁴ % of DM	31.8	32.5	32.1	30.2	1.03	0.74	0.51	0.54
Ca, % of DM	1.20	1.11	1.05	1.08	0.04	0.10	0.54	0.27
P, % of DM	0.49	0.43	0.49	0.53	0.02	0.07	0.08	0.09
K, % of DM	2.22	2.33	2.19	2.15	0.09	0.38	0.76	0.55
Mg, % of DM	0.39	0.38	0.36	0.37	0.01	0.27	0.85	0.35
Na, % of DM	0.49	0.43	0.46	0.50	0.02	0.56	0.71	0.14

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa shorter chop and oat longer chop; ASOS = alfalfa short chop and oat short chop.

²Nutrient compositions of experimental diets were measured for each experimental period (n = 4). AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

³ADIP = acid detergent insoluble protein.

⁴NFC calculated as 100 – % CP – % NDF – % ether extract – % ash.

The PSPS was shaken 40 times (5 times in each direction, twice; Kononoff et al., 2003). The contents of each fraction were weighed and analyzed for DM and NDF

Table 2. Ingredient composition of energy supplement and protein supplement (% of DM)

Ingredient	Energy supplement	Protein supplement
Rolled barley	54.0	—
Luprosil salt (calcium propionate)	0.2	—
Protein pellet ¹	1.8	—
Dairy supplement ²	40.0	—
Vegetable oil	4.0	—
Dried distillers grain	—	42.0
Fish meal	—	7.0
Canola meal	—	22.7
Soybean meal	—	20.0
Beet molasses	—	3.0
Niacin	—	0.3
Sodium bicarbonate	—	5.0

¹Protein pellets contain (DM basis) 46.1% soybean meal, 2.6% wheat shorts, 40.0% canola meal, 5.0% oat hulls, 0.3% pellet binder, 1.0% cane molasses, and 5.0% corn gluten meal.

²Dairy supplement contains (DM basis) 0.13% vitamin A, D, and E premix (vitamin A, 16,800 IU/kg; vitamin D, 2,215 IU/kg; vitamin E, 75 IU/kg, DM basis), 0.13% trace mineral premix, 2.6% soybean meal, 0.06% selenium, 39.1% wheat shorts, 5.0% distillers grain, 17.5% canola meal, 15.0% ground wheat, 1.7% dicalcium phosphate, 1.6% salt, 2.0% dynamate, 0.3% pellet binder, 1.0% cane molasses, 3.7% calcium carbonate, and 10.0% corn gluten meal.

as described earlier. Physically effective fiber was determined using 3 techniques: 1) as the proportion of the dietary NDF retained by the PSPS sieves (**peNDF_{NDF}**); 2) as the proportion of dietary DM retained by the PSPS sieves multiplied by the dietary NDF content (**peNDF_{PS}**); 3) using tabular values (**peNDF_M**) for the physical effectiveness of feeds as recommended by Mertens (1997). The geometric mean and standard deviation of feed samples were obtained by fitting PSPS distribution with a lognormal equation, as described by Kononoff et al. (2003). Sorting was calculated as described by Leonardi and Armentano (2003) and Leonardi et al. (2005) as the actual intake of each PSPS fraction expressed as a percentage of the predicted intake of this PSPS fraction. Values lower than 100% indicate selective refusals, values greater than 100% indicate preferential consumption, and a value of 100% indicates the absence of sorting.

Particle size distributions of TMR were also measured by dry sieving using a vertical oscillating test sieve shaker (EFL 1 KII, Endecotts Ltd., London, UK) equipped with a stack of 6 brass sieves and a bottom pan with a 200-mm diameter (ASTM E11, Endecotts Ltd.) arranged in descending mesh size. Sieve mesh sizes were 19, 9.5, 6.3, 4.0, 1.18, and 0.6 mm. Approximately 200 g was placed on the top screen, and the

stack of sieves was shaken until the distribution of materials did not change (approximately 15 min). The $\text{peNDF}_{>1.18}$ was determined as the proportion of DM retained on and above the 1.18-mm screen multiplied by dietary NDF.

Alfalfa silage and corn silage were analyzed for VFA, lactate, and ethanol using HPLC as described by Bhandari et al. (2007). Forage pH was also measured as described by Bhandari et al. (2007). Ammonia nitrogen concentration of silage samples was determined according to AOAC method 920.03 (AOAC, 1990).

Eating Behavior and Meal Sizes

Eight cows from 2 Latin squares were videotaped for 3 consecutive days during each sample period using 4 low-light level black and white video cameras (WV-BP 134 Panasonic), a multiplexer (WJ-FS 216 Digital Panasonic), and a time-lapse video recorder (Panasonic AG 6720A). The 4 cameras were placed about 5 m above the floor to allow complete visualization of the 2 pens. Cameras were linked to a central monitor and video recorder. Barn lights were turned off between 2200 and 0330 h. Video recording at night was conducted with seven 40-W red bulbs, providing a total light intensity of less than 3 lx. Eating and ruminating activities were determined by instantaneous scan sampling at 5-min intervals (Maekawa et al., 2002; Leonardi et al., 2005; Rotger et al., 2006). All other activities of the animals excluding the eating and ruminating activities were assigned as idle. These activities were recorded for 1 min after every 5 min and it was assumed that each activity persisted for the entire 5-min interval (Maekawa et al., 2002; Leonardi et al., 2005; Rotger et al., 2006). Total time spent chewing was calculated as the sum of eating and ruminating time. A pilot study showed that the collection coefficient between continuous monitoring and 5-min scan sampling of feeding and ruminating activities was 0.92 (S. K. Bhandari; unpublished data). This correlation coefficient compared well with that of 0.94 between continuous monitoring of feeding activities and scan sampling of feeding behavior of feedlot cattle using a 5-min interval reported by Mithöner et al. (2001).

Feed intakes of all cows were monitored continuously during each sampling period. Bunks were cleaned daily before the next feed allocation. Each feed bunk was connected to a weight acquisition system (model 4000/E, Growsafe Systems Ltd., Airdrie, AB, Canada) consisting of 400-kg load cell bars connected to an A/D converter. The output signals were recorded in a computer using the appropriate software (model 4000 data acquisition software, version 1.2 MOD, Growsafe Systems Ltd.). Meals were defined as the combination of

eating activities that were separated by intervals shorter than or equal to the meal criterion (Tolkamp and Kyriazakis, 1999; Tolkamp et al., 2000). Meal criteria were determined by fitting the log transformed intervals between eating events to 3 Gaussian distributions and determining the interval length where the 2 Gaussian distributions with the largest means intersected, as described by Tolkamp and Kyriazakis (1999) and Tolkamp et al. (2000). The maximum likelihood procedure of GENSTAT version 9.1 (VSN International Ltd., Hemel Hempstead, UK) was used for curve fitting. Meal criteria were calculated separately for each cow for on each diet. Subsequently, the duration, size, and eating rate were determined for each meal.

Rumen pH and Rumen Liquid Flow Rate Measurement

Rumen pH was measured continuously in the rumen cannulated cows from Monday at 0900 h to Saturday at 0900 h during each sampling period using indwelling pH probes as described by Gozho et al. (2005). Rumen pH was measured at 1-min intervals and data sent to a data logger for storage and used for subsequent analysis. Rumen pH data were summarized by calculating the average pH, the time below pH 6, the time below pH 5.6, the area (time $\times$ pH) below pH 6, and the area below pH 5.6 for each 24-h period, as described by Gozho et al. (2005).

Rumen fluid from all cows was collected at 4 to 5 h after the delivery of fresh feed on 2 d during each sampling period. Rumen fluid was obtained from nonfistulated cows using a Geishauser oral probe (Duffield et al., 2004). The first 200 mL of collected rumen fluid was discarded and the subsequent 50 mL of rumen fluid was kept for subsequent analysis and processing (Duffield et al., 2004). Rumen fluid from the fistulated cows was obtained from the cranial ventral region. Rumen fluid samples were centrifuged immediately after collection at $1,900 \times g$ for 10 min and the supernatant stored at -20°C until further analysis.

The rumen liquid outflow rate was measured using Cr-EDTA in the 4 rumen-cannulated cows. The method used to prepare the Cr-EDTA was that of Uden et al. (1980). A solution of Cr-EDTA in distilled water was introduced into several sites in the rumen through the ruminal cannula at 0900 h. Ruminal fluid samples were collected at 0, 2, 4, 6, 8, 12, 16, 24, 48, and 72 h postdosing from the ventral sac of the rumen. Rumen fluid samples were analyzed for the Cr concentration using the inductive coupled plasma optical emission spectroscopy (ICP-OES; Vista MPX, Varian, Walnut Creek, CA) and the liquid rate of passage from the rumen was

estimated as the slope of the regression of the natural logarithm of the concentration with time postdosing.

Blood Sampling and Analysis

Blood samples were collected at 4 to 5 h postfeeding on 2 d during each sampling period by coccygeal venipuncture in heparinized 10-mL Vacutainers. Samples were subsequently centrifuged at $1,900 \times g$ for 10 min and the plasma was aspirated and stored at -20°C until further analysis. Blood plasma was analyzed for glucose, urea, and lactate using a Nova Stat Profile M blood gas and electrolyte analyzer (Nova Biomedical Corporation, Waltham, MA) as described by Bhandari et al. (2007).

VFA, Ammonia, and Rumen Fluid Marker Analysis

Frozen rumen fluid samples were thawed at room temperature and 1 mL of 25% meta-phosphoric acid solution was added to 5 mL of rumen fluid. The tubes were vortexed and placed in a -20°C freezer for 17 h. Thawed samples were centrifuged for 10 min at $1,900 \times g$. Approximately 2 mL of supernatant was decanted into a clean, dry vial. The samples were capped and placed into the autosampler device (model 8100, Varian) for analysis. Concentrations of VFA were determined by gas chromatography as described by Bhandari et al. (2007). Ammonia nitrogen concentration of rumen fluid samples was determined as described by Bhandari et al. (2007).

Milk Yield and Composition Analysis

Cows were milked twice daily in their stalls and milk production was measured using Tru-Test regulation meters (Westfalia Surge, Mississauga, ON, Canada) that were accurate within 5% or 0.3 L. Milk samples were collected from 4 consecutive milkings in 50-mL vials in each collection period and preserved with 2-bromo-2-nitropropane-1,3 diol. Milk samples were stored at 4°C until analyzed for fat and protein at the laboratory of the Dairy Farmers of Manitoba (Winnipeg, MB, Canada) by near infrared analysis using the MilkoScan 303AB (Foss Electric, Hillerød, Denmark). This infrared analysis was calibrated by the Babcock method for milk fat analysis (method 989.04; AOAC, 1990) and the Kjeldahl method for nitrogen/protein nitrogen analysis in milk (method 991.22; AOAC, 1990).

Statistical Analysis

An ANOVA of data on rumen fluid composition, blood plasma variables, milk production, feed intakes, feed-

ing behavior variables, and sorting was conducted using MIXED procedure (SAS Institute, 1990). The effects of alfalfa chop length and corn chop length and their interaction were considered fixed. The effects of square, cow within square, period, and day within period were considered random. Day within period was considered a repeated measure. An ANOVA of weekly averages of chemical and physical characteristics of experimental diets was also conducted with the MIXED procedure (SAS Institute, 1990), considering the effects of alfalfa chop length and corn chop length and their interaction as fixed effects.

An ANOVA of the proportion of the daily DMI consumed within 3-h periods relative to feed delivery was conducted using the MIXED procedure (SAS Institute, 1990) as recommended by Wang and Goonewardene (2004) for the analysis of animal experiments with repeated measures. The effects of alfalfa chop length and corn chop length and their interaction were considered fixed, and cow within square was considered as the experimental unit.

Data on meal sizes, meal durations and eating rates were log transformed before statistical analysis. Statistical significance was set at $P \leq 0.05$; trends were discussed at $P \leq 0.10$. Differences among treatment means were tested for significance using Tukey's multiple range test (SAS Institute, 1990). Reported standard errors are those used for the comparison of treatment means. The 95% confidence intervals least squares treatment means of sorting were calculated to determine if these means differed significantly from 100%.

Rumen liquid outflow rate was measured using the marker Cr-EDTA and was estimated using the following formula:

$$C(t) = C_0 e^{-kt},$$

where $C(t)$ = marker concentration in rumen at time t ; C_0 = marker concentration in rumen at time of infusion ($t = 0$); and k = rumen liquid outflow rate (outflow/volume) per time unit.

RESULTS

Chemical and Physical Compositions of Forages and Diets

The chemical and physical compositions of the experimental forages are given in Tables 3 and 4, respectively. Table 3 shows the shorter chop of both forages resulted in lower silage pH and greater silage VFA than the longer chop of these silages. The other nutrients that were measured were similar for both chop lengths of these silages. Reducing the chop length of alfalfa silage and oat silage from 19 to 6 mm reduced the proportion

Table 3. Nutrient composition and silage fermentation profile ($\pm$ SD) of the silages included in the experimental diets

Item	Silage ¹			
	AL	AS	OL	OS
Nutrient composition ²				
DM, %	42.1 (1.4)	40.3 (2.7)	29.6 (0.7)	30.0 (1.9)
CP, % of DM	16.9 (0.9)	17.3 (0.2)	10.5 (0.5)	11.1 (0.8)
NDF, % of DM	48.4 (2.2)	48.0 (0.8)	59.4 (1.9)	59.9 (4.2)
ADIP, ³ % of DM	1.7 (0.1)	1.4 (0.1)	1.0 (0.1)	0.8 (0.1)
ADF, % of DM	34.8 (2.2)	33.8 (1.7)	36.8 (1.5)	36.0 (1.2)
Ether extract, % of DM	2.0 (0.3)	2.0 (0.3)	3.2 (0.1)	3.1 (0.1)
Ash, % of DM	11.3 (0.3)	13.1 (0.3)	9.3 (0.2)	9.7 (0.2)
NFC, ⁴ % of DM				
Ca, % of DM	1.30 (0.06)	1.37 (0.16)	0.41 (0.22)	0.41 (0.19)
P, % of DM	0.27 (0.02)	0.29 (0.02)	0.33 (0.04)	0.36 (0.02)
K, % of DM	3.00 (0.23)	3.13 (0.28)	2.05 (0.27)	2.41 (0.27)
Mg, % of DM	0.39 (0.03)	0.41 (0.04)	0.26 (0.08)	0.26 (0.03)
Na, % of DM	0.05 (0.01)	0.04 (0.00)	0.29 (0.07)	0.32 (0.03)
Fermentation profile ⁵				
pH	6.0 (1.5)	4.9 (0.4)	5.4 (1.3)	4.6 (0.2)
VFA (% of DM)	4.7 (1.8)	5.3 (0.7)	3.1 (1.9)	4.4 (0.3)
Lactic acid (% of DM)	2.3 (1.9)	3.9 (0.8)	0.8 (0.5)	1.3 (1.0)
Ammonia (% of CP)	18.2 (6.9)	14.2 (6.2)	13.2 (2.5)	17.3 (1.2)

¹AL = alfalfa longer chop (19 mm); AS = alfalfa shorter chop (6 mm); OL = oat longer chop (19 mm); OS = oat shorter chop (6 mm).

²Nutrient composition of forages were determined for each experimental period (n = 4).

³ADIP = acid detergent insoluble protein.

⁴NFC calculated as 100 – % CP – % NDF – % ether extract – % ash.

⁵Fermentation profile of the forages were determined for each experimental period (n = 4).

of silage retained by the 19-mm screen of the PSPS from 39.2 to 20.6% of DM and from 25.7 to 12.2% of DM, respectively (Table 4). The reduction in forage chop length increased the proportions of silage retained by

the 8-mm screen of the PSPS from 44.3 to 54.7% of DM and from 56.1 to 62.6% of DM, respectively. Reducing the chop length of alfalfa silage and oat silage at harvest from 19 to 6 mm reduced the actual average particle

Table 4. Penn State particle size analysis, geometric mean (X_{gm}), and standard deviation (S_{gm}) ($\pm$ SD) of shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

PSPS distribution ²	Silage ¹			
	AL	AS	OL	OS
Percent retained, as-fed basis				
Top screen (19 mm)	39.3 (7.1)	20.6 (2.7)	29.4 (5.6)	13.3 (2.5)
Second screen (8 mm)	45.1 (3.9)	55.5 (2.7)	56.1 (3.1)	63.0 (4.0)
Third screen (1.18 mm)	14.2 (3.9)	22.5 (4.1)	13.9 (5.1)	23.1 (5.7)
Bottom pan	1.4 (0.3)	1.4 (0.7)	0.6 (0.8)	0.6 (0.7)
Percent retained, DM basis				
Top screen (19 mm)	39.2 (7.0)	20.6 (2.7)	25.7 (5.6)	12.2 (2.9)
Second screen (8 mm)	44.3 (3.2)	54.7 (2.7)	56.1 (3.1)	62.6 (4.1)
Third screen (1.18 mm)	14.4 (4.0)	23.0 (4.0)	17.0 (5.8)	24.2 (5.8)
Bottom pan	2.2 (0.4)	1.8 (1.0)	1.8 (1.4)	1.1 (1.2)
As-fed basis ³				
X_{gm} , mm	14.2 (1.6)	10.9 (1.0)	13.4 (1.6)	10.4 (1.1)
S_{gm} , mm	2.2 (0.1)	2.1 (0.1)	2.0 (0.1)	2.0 (0.1)

¹AL = alfalfa longer chop (19 mm); AS = alfalfa shorter chop (6 mm); OL = oat longer chop (19 mm); OS = oat shorter chop (6 mm).

²Penn State Particle Separator (PSPS) distributions of experimental silages were calculated for each period (n = 4) for each treatment.

³ X_{gm} = geometric mean length, calculated on an as-fed basis (Kononoff and Heinrichs, 2002); S_{gm} = standard deviation, calculated on an as-fed basis (Kononoff and Heinrichs, 2002).

Table 5. Penn State Particle Separator analysis, physical effective fiber content, geometric mean (X_{gm}), and standard deviation (S_{gm}) and sorting of experimental diets containing a shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Percent retained, as-fed basis								
Top screen (19 mm)	23.1	17.3	16.4	10.0	2.15	<0.01	<0.05	0.90
Second screen (8 mm)	52.5	52.7	56.2	56.4	1.22	<0.05	0.82	0.98
Third screen (1.18 mm)	22.2	27.5	25.0	30.6	2.34	0.22	<0.05	0.95
Bottom pan	2.2	2.5	2.4	3.0	0.30	0.13	0.30	0.59
Percent retained, DM basis								
Top screen (19 mm)	18.5	14.5	12.8	7.9	1.83	<0.01	<0.05	0.81
Second screen (8 mm)	52.9	54.4	56.5	56.7	2.49	0.05	0.56	0.63
Third screen (1.18 mm)	25.7	28.2	27.6	31.8	1.78	0.29	0.21	0.75
Bottom pan	2.9	3.0	3.2	3.8	0.51	0.20	0.37	0.48
NDF retained in fraction, % of DM								
Top screen (19 mm)	53.9	51.5	54.7	56.3	0.81	<0.01	0.62	0.12
Second screen (8 mm)	34.4	36.9	34.2	35.1	0.96	0.31	0.09	0.42
Third screen (1.18 mm)	29.3	32.2	30.0	33.6	0.67	0.16	<0.001	0.61
Bottom pan	34.6	36.0	35.7	35.5	0.64	0.62	0.33	0.25
Physical effective fiber and particle length								
peNDF _{PS} , ³ % of DM	24.5	23.4	23.7	21.6	0.25	0.20	0.37	0.48
peNDF _{NDF} , ⁴ % of DM	28.1	27.5	26.3	24.3	1.47	0.11	0.41	0.65
peNDF _{>1.18} , ⁵ mm	30.2	29.9	30.2	27.9	1.16	0.35	0.24	0.37
X_{gm} , ⁶ mm	10.9	9.7	9.9	8.6	0.45	<0.05	<0.05	0.95
S_{gm} , ⁷ mm	2.2	2.2	2.2	2.2	0.03	0.13	0.90	0.90

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat short chop.

²Penn State Particle Separator distributions of experimental diets were calculated for each period (n = 4) for each treatment. AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

³peNDF_{PS} = proportion of DM retained by the 19- and 8-mm PSPS screens multiplied by dietary NDF content.

⁴peNDF_{NDF} = proportion of NDF retained by the 19- and 8-mm PSPS screens.

⁵peNDF_{>1.18mm} = proportion of NDF retained by ≥1.18-mm screens.

⁶ X_{gm} = geometric mean length, calculated on an as-fed basis (Kononoff and Heinrichs, 2002).

⁷ S_{gm} = standard deviation, calculated on an as-fed basis (Kononoff and Heinrichs, 2002).

length from 14.4 to 10.0 mm, and from 13.4 to 10.4 mm, respectively.

The chemical and physical compositions of the experimental diets are given in Tables 1 and 5, respectively. Table 1 shows that DM was greater and that the CP tended to be greater in the diets containing the shorter chop oat silage compared with the diets containing the longer chop oat silage. Diets did not differ in the other nutrients that were measured. Reducing the chop length of both silages reduced the proportion of the diet retained by the 19-mm PSPS screen from 18.5 to 7.9% of DM. It also increased the proportion of the diet retained by the 8-mm PSPS screen from 52.9 to 56.7 of DM, and reduced the average particle length from 10.9 to 8.6 mm (Table 5). For all diets, the NDF contents of the fractions retained by the 19- and 8-mm PSPS screens were greater than those of the fractions retained by the 1.18-mm screen and the bottom pan. As a result, values for peNDF_{NDF} were greater than those for peNDF_{PS}. Values for peNDF_{>1.18} mm were greater

than those for peNDF_{NDF} and peNDF_{PS}. Despite an effect of alfalfa silage chop length and oats silage chop length on the geometric mean of the feed particle length, both chop lengths did not significantly affect peNDF_{PS}, peNDF_{NDF}, or peNDF_{>1.18}.

Feed and Water Intake and Feeding Behavior

Reducing the chop length of alfalfa did not affect DMI, but reducing the chop length of oats increased DMI from 19.4 to 21.2 kg/d across alfalfa chop lengths (Table 6). Forage chop length did not affect water intake (Table 6). The data on the sorting of the cows by screen of the PSPS is given in Table 7. The least squares means of the sorting of the fraction of the diets retained by the 19-mm screen was lower than 100% for all diets. The least squares means of the sorting of the fractions retained by the 1.18-mm screen and the 8-mm screen were greater than 100% for all diets, with the exception of the sorting of the fraction retained by the 1.18-mm

Table 6. Dry matter intake, Orts, and water intake of cows fed experimental diets containing shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
DMI, kg/d	19.0	21.3	19.8	21.1	0.48	0.50	<0.001	0.34
Orts, % of feed provided	11.7	6.4	7.1	6.5	2.67	0.38	0.26	0.37
Water intake, L/d	77.8	82.3	82.4	81.6	2.00	0.33	0.36	0.20

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat shorter chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

screen of the diets containing longer chop alfalfa silage and shorter chop oats silage. However, this sorting ranged only from 101.3 to 103.8%. The sorting of the fraction retained by the bottom pan also differed significantly from 100% and ranged from 154.5 to 173.5% among diets. This shows that cows sorted against feed particles that were longer than 19 mm and sorted in favor of feed particles shorter than 8 mm. This sorting against feed particles longer than 19 mm was greater for the diets containing the longer chop oat silage compared with the diets containing the shorter chop oat silage. The selection in favor of dietary particles with a length between 1.18 and 8 mm was greater ($P = 0.03$) for the diets containing the longer chop alfalfa silage compared with diets containing the shorter chop alfalfa silage.

Times spent eating, ruminating, chewing, and chewing per kilogram of DM were not affected by forage chop length and averaged 361, 575, 936 min/d, and 49.7 min/kg of DM, respectively, across diets (Table 8). The meal criterion did not differ among diets (Table 9). As a result, a pooled criterion of 21.3 min was used for the determination of the meal characteristics. The particle lengths of alfalfa silage and oat silage did not affect the number of meals per day, nor the average daily meal duration, meal size, and eating rate (Table 9). During the first meal after feed delivery, more feed was eaten,

and the duration of eating was longer compared with other meals. Reducing the chop length of both forages reduced the duration and size of this first meal.

The proportions of daily DMI consumed within 3-h periods relative to feeding delivery are given in Table 10. Period after feeding affected the proportion of the daily DMI consumed during these periods. The proportion of the daily intake of TMR eaten within 3 h after feed delivery was greater than that eaten during any other 3-h interval. The interactions between alfalfa chop and period after feeding and oat chop and period after feeding were both significant ($P < 0.0005$ and $P < 0.005$, respectively). Reducing the chop length of alfalfa silage and oat silage both reduced the proportion of the daily DMI of TMR eating during the first 3 h after feed delivery.

Rumen Fermentation and Blood Variables

The chop lengths of alfalfa silage oat silage did not affect the average daily rumen pH, the durations of time during which rumen pH was below pH 6 and below pH 5.6, and the areas below pH 6 and below pH 5.6 (Table 11). Rumen liquid outflow rate was also not affected by the forage particle size in our study and varied from 11.3 to 12.1%/h among diets. Reducing particle sizes of alfalfa silage and oat silage did not affect the

Table 7. Sorting (%) of cows of Penn State Particle Separator fractions of the experimental diets containing shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Sorting ¹	Diet ²				SE	Effect ³		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Top screen (19 mm)	89.3	85.2	89.0	81.3	2.70	0.45	0.05	0.50
Second screen (8 mm)	102.8	102.0	101.8	102.0	0.34	0.16	0.47	0.17
Third screen (1.18 mm)	103.0	103.8	101.3	102.0	0.73	0.03	0.32	0.95
Bottom pan	162.5	173.5	168.3	154.5	12.4	0.60	0.91	0.34

¹Sorting by screen was calculated on as-fed basis as $[100 \times (\text{actual intake}/\text{predicted intake})]$; Leonardi et al. (2005).

²ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat shorter chop.

³AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

Table 8. Time spent eating, ruminating, and chewing (eating and ruminating) of cows recorded by video monitoring (with scan sampling at 5-min intervals) fed experimental diets containing shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Eating, h/d	360	382	353	352	12.6	0.17	0.31	0.29
Ruminating, min/d	571	567	565	596	16.4	0.37	0.27	0.17
Total chewing								
Min/d	931	949	917	948	19.7	0.68	0.13	0.71
Min/kg of DM	50.9	48.8	49.7	49.1	5.16	0.59	0.16	0.43

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat shorter chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

concentrations of VFA, the acetate to propionate ratio, and ammonia in the rumen (Table 12). The plasma concentrations of glucose, urea, and lactate were also not affected by the chop lengths of oat silage and alfalfa silage (Table 13).

Milk Production and Composition

The chop length of alfalfa and oat silage did not affect milk yield, milk fat percentage, milk protein percentage, or milk protein yield (Table 14). Reducing the chop length of oat silage tended to increase ($P = 0.09$) milk fat yield, whereas the chop length of alfalfa silage did not affect milk fat yield. Daily milk yield, milk fat percentage, and milk protein percentage averaged 36.1 kg/d, 3.00%, and 3.16%, respectively, across all diets.

DISCUSSION

Dairyland Laboratories (2007) reported normal ranges of the pH of legume silages and small grain silages of between 4.2 and 5.5 and between 3.7 and 5.5,

respectively. The pH of the longer chop alfalfa silage was higher than the range for legume silages, but the pH of the shorter chop alfalfa silage fell within this range. The pH values of both oat silages were within the normal range for small grain silages silage reported by Dairyland Laboratories (2007).

Kung and Shaver (2000) recommended target levels for pH, ammonia-N content, and lactate content of legume silage of pH 4.0 to 4.3, lower than 12% of CP, and 4.0 to 6.0% of DM, respectively. Kononoff and Heinrichs (2003a) reported a pH, ammonia-N content, and lactate content of alfalfa silage of 4.7, 12.7% of CP, and 5.9% of DM, respectively. Hence, the pH and ammonia-N content of the alfalfa silages in our study were greater and the lactate contents of alfalfa silages in our study were lower than recommended by Kung and Shaver (2000) and found by Kononoff and Heinrichs (2003a). Nevertheless, the pH and ammonia-N content of the alfalfa silage chopped at 6 mm were lower and the lactate content of this silage was greater than the 5.1, 4.7% of DM, and 17.3% of CP found by Bhandari et al. (2007) in alfalfa silage chopped at 10 mm. Thus, reduc-

Table 9. Meal patterns of cows fed experimental diets containing a shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Number of meals/d	8.23	8.09	8.47	7.24	0.62	0.47	0.20	0.12
Meal criterion, min	24.5	18.9	19.6	22.2	4.53	0.87	0.76	0.39
All meals								
Meal duration, min	35.4	36.8	35.8	35.4	3.84	0.19	0.27	0.80
Meal size, kg of DM	2.42	2.65	2.30	2.65	0.25	0.47	0.26	0.21
Eating rate, g of DM/min	55.9	57.3	60.3	68.3	8.02	0.90	0.33	0.51
First meal								
Meal duration, min	138.6	136.7	127.4	103.5	7.20	<0.05	0.03	0.09
Meal size, kg of DM	8.77	8.30	8.00	7.20	0.57	0.02	0.04	0.66
Eating rate, g of DM/min	63.3	60.7	62.8	69.6	5.15	0.27	0.49	0.46

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat short chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

Table 10. Proportion of DMI consumed within 3-h periods relative to feed delivery of high-yielding dairy cows fed with diets containing a shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Time relative to feed delivery, h	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
0 to 3	42.1	36.3	36.1	30.8	2.29	<0.05	<0.05	0.91
3 to 6	18.2	21.5	19.3	17.4	1.68	0.37	0.69	0.12
6 to 9	12.6	10.0	12.3	10.5	1.44	0.95	0.06	0.74
9 to 12	9.3	10.9	13.2	17.9	1.66	<0.01	0.07	0.35
12 to 15	11.9	11.7	9.2	10.4	1.61	0.23	0.76	0.67
15 to 18	2.1	3.5	2.0	2.3	0.81	0.40	0.31	0.46
18 to 21	2.4	2.7	2.2	3.7	0.78	0.57	0.24	0.45
21 to 24	1.4	3.3	5.6	7.1	0.99	<0.01	0.10	0.82

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat short chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

ing the chop length of alfalfa silage and oat silage improved the fermentation profile.

Kung and Shaver (2000) did not give recommendations for the fermentation profile of oat silage, but recommended target levels for the pH, ammonia-N content, and lactate content of corn silage of 4.0 to 4.5, <8% of CP, and 5.0 to 10.0% of DM, respectively. The average pH, ammonia-N content, and lactate content of barley silage reported by Yang and Beauchemin (2006a) were 3.92, 4.1% of CP, and 6.7% of DM, respectively. Thus, the pH and ammonia-N content of the alfalfa silages in our study were greater and the lactate contents of oat silages in our study were lower than recommended by Kung and Shaver (2000). These values were also lower than those observed by Yang and Beauchemin (2006a) for barley silage. However, the pH of the oat silage chopped at 6 mm was lower than the 5.0 reported by Bhandari et al. (2007) for corn silage chopped at 10 mm and very close to the upper limit of

the corn silage pH recommended by Kung and Shaver (2000).

The proportions retained by the 19-mm screen were much greater than the 10 to 20% and the 3 to 8% recommended for haylage and corn silage, respectively, by Heinrichs and Kononoff (2002). The proportions of the silages retained by the 8-mm screen agree with the recommendations from Heinrichs and Kononoff (2002). The NDF content of all diets was greater than the minimum of 34% of DM recommended by Beauchemin (1991) for barley-based diets. The proportion of the diet retained by the 19-mm PSPS screen of all diets, with the exception of the diet containing the shorter chop of both silages, was greater than recommended by Heinrichs and Kononoff (2002). The proportion of the diet retained by the 8-mm PSPS screen was greater than the proportion recommended by Heinrichs and Kononoff (2002) for all diets. Reducing the chop lengths of alfalfa silage and oats silage decreased the geometrical aver-

Table 11. Rumen parameters based on continuous rumen pH monitoring using indwelling probes in cows fed diets containing shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Average daily pH	6.21	6.22	6.27	6.27	0.07	0.30	0.94	0.94
T < 6, min/d ³	490.3	482.1	394.1	434.8	94.9	0.33	0.82	0.73
T < 5.6, min/d ⁴	197.2	128.1	120.6	129.4	59.6	0.41	0.50	0.39
A < 6, min × pH/d ⁵	172.6	123.9	122.0	129.4	45.6	0.51	0.55	0.42
A < 5.6, min × pH/d ⁶	37.0	14.8	21.7	19.5	12.2	0.56	0.21	0.29
Rumen liquid outflow rate, %/h	11.3	11.8	12.1	11.5	0.8	0.66	0.89	0.35

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat short chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

³T < 6 = time below rumen pH 6.0 per day.

⁴T < 5.6 = time below rumen pH 5.6 per day.

⁵A < 6 = area below rumen pH 6.0 per day.

⁶A < 5.6 = area below rumen pH 6.0 per day.

Table 12. Rumen fluid composition based on spot sampling using a stomach tube for diets containing a shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
VFA, mM								
Total	121.0	125.8	116.2	126.9	5.56	0.91	0.34	0.64
Acetate (A)	77.6	82.9	74.1	83.5	4.85	0.89	0.37	0.70
Propionate (P)	25.6	23.3	24.1	24.4	1.28	0.92	0.54	0.33
Butyrate	13.7	14.8	13.9	14.6	0.74	0.93	0.21	0.66
Other	3.9	4.8	4.0	4.4	0.27	0.93	0.03	0.21
A:P	3.4	3.7	3.4	3.5	0.27	0.76	0.75	0.77
Ammonia, mg/dL	10.9	11.6	12.1	11.1	0.65	0.73	0.56	0.21

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa shorter chop and oat longer chop; ASOS = alfalfa shorter chop and oat short chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

age feed particle length of the diets, but did not affect peNDF_{PS} , $\text{peNDF}_{>1.18}$, and $\text{peNDF}_{\text{NDF}}$. One reason for the absence of an effect on physically effective fiber was that a reduction of the chop length of the alfalfa silage decreased the proportion of the diet retained by the 19-mm screen, but increased the proportion of the diet retained by the 8-mm screen. As the fractions retained by both of these screens were considered physically effective, such a shift between these screens did not affect values for physically effective fiber. It has been suggested that 1.18 mm is a threshold for the retention of feed particles in the rumen in the reticulum and the rumen (Poppi et al., 1985; Mertens, 1997). This particle length might, therefore, affect chewing behavior. This is also a reason why a 1.18-mm screen was included in the PSPS (Kononoff and Heinrichs, 2002). Hence, the absence of an effect of forage chop length on chewing behavior might be related to the absence of a forage chop length effect on $\text{peNDF}_{>1.18}$. As the total chewing time and rumen pH, as well as the various measures of physically effective fiber, did not differ among diets, it was not possible to determine which measure of physically effective fiber is the best predictor of rumen buffering and rumen pH. The absence of a diet effect on chewing time and rumen pH also prevented assessing if the average feed particle length is a better indicator

of rumen buffering that the measures of physically effective fiber used in this study.

The absence of an effect of the chop length of alfalfa silage on DMI is in agreement with Bhandari et al. (2007), who also found that reducing the chop length of alfalfa silage from 19 to 10 mm did not affect DMI. However, in their study a similar reduction in the chop length of corn silage increased DMI. In that study, the lower DMI with the 19-mm corn silage chop length was attributed to a failure to fully fractionate corn cobs at this chop length, which resulted in unpalatable chunks. This does not explain the increased DMI resulting from the reduction in the oat silage chop length in our study, because the longer chop length did not result in unpalatable chunks. Krause et al. (2002a) reduced the average geometric particle length of alfalfa silage from 13.6 to 3.7 mm and incorporated these silages into a diet containing 39.3% of DM of this silage. They also found that this reduction did not affect DMI. However, Kononoff and Heinrichs (2003a) found that reducing the average geometric particle length of alfalfa haylage from 18.1 to 8.9 mm and including 50% of DM of alfalfa haylage in a TMR increased DMI. Reasons for this discrepancy between the study from Kononoff and Heinrichs (2003a) and other studies may be attributed to the longer alfalfa particle length and the greater dietary

Table 13. Concentrations of metabolites in blood plasma for experimental diets containing shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Glucose, mM	3.78	3.61	3.75	3.78	0.06	0.13	0.11	0.03
Lactate, mM	1.05	0.89	0.89	0.87	0.08	0.11	0.11	0.25
Urea, mM	6.0	6.0	5.9	5.8	0.16	0.15	0.76	0.78

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat shorter chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

Table 14. Milk production of cows fed experimental diets containing a shorter (6 mm) or longer (19 mm) chop lengths of alfalfa and oat silages

Item	Diet ¹				SE	Effect ²		
	ALOL	ALOS	ASOL	ASOS		AC	OC	AC × OC
Milk yield, kg/d	35.1	36.7	36.3	36.2	1.10	0.59	0.36	0.28
Milk component								
Fat, %	2.95	3.06	2.99	3.03	0.14	0.91	0.42	0.78
Fat yield, kg/d	1.03	1.12	1.08	1.11	0.04	0.53	0.09	0.31
Protein, %	3.18	3.14	3.16	3.18	0.04	0.71	0.74	0.28
Protein yield, kg/d	1.09	1.15	1.13	1.16	0.04	0.37	0.12	0.58

¹ALOL = alfalfa longer chop and oat longer chop; ALOS = alfalfa longer chop and oat shorter chop; ASOL = alfalfa short chop and oat longer chop; ASOS = alfalfa short chop and oat short chop.

²AC = alfalfa chop effect; OC = oat chop effect; AC × OC = interaction effect of alfalfa and oat chop lengths.

inclusion rate of alfalfa in their study. Also, in contrast to our results, Krause and Combs (2003) observed a reduction in DMI when the particle length of alfalfa silage was decreased. This might be explained by the very low rumen pH resulting from feeding the diets with a short particle length of alfalfa, which can result in SARA and decreased feed intake (Stone, 2004).

With the exception of a study by Leonardi et al. (2005), information on the effects of particle length of oat silage in cattle is lacking. As oats and barley are both cereal grains, barley silage is more representative of oat silage than corn silage. In agreement with our study, Leonardi et al. (2005) found that a reduction in average particle length of TMR from 6.68 to 4.35 mm, achieved by reducing the average particle length of oat silage, increased DMI of dairy cows fed diets containing 49.8% of DM as concentrate and 25.1% of DM as oat silage. Yang and Beauchemin (2006b) reduced the chop length of barley silage from 9.5 to 4.8 mm and incorporated these silages in a TMR containing 46.6% of DM as barley silage and barley grain-based concentrate. In contrast to our study, these authors found that this reduction in the chop length of barley silage did not affect the DMI of dairy cows. Conversely, Kononoff et al. (2000) found that reducing the chop length of barley silage from 9.0 to 4.8 mm reduced the DMI of dairy cows fed TMR diets 55% with DM as barley grain concentrate. The discrepancies between the studies conducted by Kononoff et al. (2000) and Yang and Beauchemin (2006ab) might be explained by differences in chop length of the silage. As indicated above, Kononoff et al. (2000) and Yang and Beauchemin (2006ab) used a shorter chop length with a narrower range of particle size length than that of the current study. In our study the DMI ranged from 3.11 to 3.49% of BW/d. This range is similar to those reported by Kononoff and Heinrichs (2003a) and Yang and Beauchemin (2006a,b).

The absence of an effect of forage chop length on chewing behavior disagrees with several earlier stud-

ies. Krause et al. (2002b) found that reducing the particle length of the alfalfa silage from 13.6 to 3.7 mm reduced the time spent eating and time spent ruminating from 300 to 232 min/d and from 468 to 351 min/d, respectively. These authors also found that time spent chewing was reduced from 30.9 to 24.9 min/d, when the alfalfa silage was incorporated in diets containing 36.3% of DM as either high-moisture shelled corn or dried cracked shelled corn and 39.3% of DM alfalfa silage. Kononoff and Heinrichs (2003a) fed TMR containing 50% of DM of alfalfa haylage and 50% of DM as concentrate to lactating dairy cows and found that reducing the average length of the alfalfa haylage from 18.1 to 8.9 mm reduced time spent eating from 298 to 262 min/d. In their study, reducing the alfalfa haylage particle length did not affect time spent ruminating, which averaged 480 min/d across diets, but time spent chewing (eating and ruminating) per kilogram of DMI was reduced from 37.9 to 31.2/kg of DM. Yang and Beauchemin (2006a) fed TMR containing 46.1% of DM as barley silage and 53.9% of DM as concentrate and observed that reducing the chop length of barley silage from 9.5 to 4.8 mm did not affect time spent eating, but reduced time spent ruminating and total time spent chewing from 440 to 363 min/d and from 719 to 622 min/d, respectively, and reduced time spent chewing per kilogram of DMI from 38.3 to 32.5 min/kg of DM. The discrepancies between our study and the earlier studies might be explained by the longer times spent eating, ruminating, and chewing in our study. When the physically effective fiber content of a diet fully stimulates chewing, further increases in physically effective fiber do not further increase chewing activity (Mertens, 1997). Hence, a physiological limit might exist, above which an increase in dietary particle length no longer increases chewing. As such, all of the diets in our study might have been above that limit.

The high DMI in the 3 h after feed delivery compared with that during any other 3-h period agrees with sev-

eral studies that showed that provision of fresh feed stimulated eating of dairy cows in tie-stalls and free-stalls (Tolkamp et al., 2000; Beauchemin et al., 2002; De Vries et al., 2003). During the first 3 h after feed delivery the DMI of diets containing the longer chop of alfalfa silage and oat silage were greater than that of diets containing the shorter chop of these silages. This agrees with the observation that the duration and size of the first meal after feed delivery was also reduced when forage chop length decreased.

Despite an effect of forage chop length on the first meal after feed delivery, it did not affect the number of meals per day, or the daily averages of meal duration, meal size, and eating rate. This difference in impact of forage chop length on the size and duration of the first meal after feed delivery, but not on the average size and duration of meals, might be explained by the comparative large size of this first meal, because the difference in size might result in differences in the mechanism regulating meal size. However, as daily DMI did not differ among diets, cows compensated for a smaller meal after feed delivery by increasing feed intake later in the day.

The absence of an effect of forage chop length on the daily averages of meal size and meal duration agrees with the absence of an effect of forage chop length on time spent eating. Other studies examining the effect of forage particle length did not measure meal patterns. This complicates comparisons among these studies. Using a 20-min meal criterion, which is similar to the 21.3-min meal criterion used in our study, Beauchemin et al. (2002) reported that lactating dairy cows in a tie-stall on TMR had 10 to 11 meals per day, with average meal size ranging from 1.86 to 1.91 kg of DM, average meal duration ranging from 36 to 39 min, and average eating rate ranging from 48 to 57 g of DM/min among diets. Dado and Allen (1994) also reported that dairy cows had on average 11 meals per day and an eating rate of 75 g of DM/min. Hence, the numbers of meals per day reported in the current study were lower than that reported by Dado and Allen (1994) and Beauchemin et al. (2002). The meal sizes were greater, and the meal durations were similar in our study compared with that of Beauchemin et al. (2002), and the eating rates (60.7 to 69.6 g of DM/min) were in between the values reported by Dado and Allen (1994) and Beauchemin et al. (2002). Using an individual meal criterion of 44.7 ± 2.1 min for cows in a free-stall offered a TMR containing 58% DM, Tolkamp et al. (2000) observed averages for meal duration and daily number of meals of 36.9 min and 6.1, respectively. As housing, meal criterion, and diets varied between our study and that of Tolkamp et al. (2000), it cannot be concluded that one

of these factors was responsible for observed differences in the daily number of meals between these 2 studies.

The threshold rumen pH below which SARA occurs is under debate. Gozho et al. (2005) suggested that a rumen pH lower than 5.6 for 180 min/d is indicative of SARA, but rumen pH thresholds of 5.5, 5.8, and 6.0 have also been used in the diagnosis of SARA (Krause et al., 2002b; Beauchemin et al., 2003; Yang and Beauchemin, 2006a). The duration of the rumen pH below 5.6 was greater than 120 min/d for the all diets. Hence, it cannot be excluded that these diets did not induce SARA. Also, the milk fat percentages of all diets were low and an inversion of the milk fat percentage and milk protein percentage occurred for all diets, which suggest SARA (Kleen et al., 2003; Stone, 2004). The nutrient composition of the diets, however, did not suggest that cows were at risk for SARA, because dietary NDF content was greater than 34% of DM, which has been identified as the minimum required dietary NDF content to prevent SARA in barley-based diets (Beauchemin, 1991). Furthermore, the diets were coarser than recommended by Heinrichs and Kononoff (2002). Cows spent more time chewing than in the studies by Kononoff and Heinrichs (2003a), Krause et al. (2002b), and Yang and Beauchemin (2006a), in which SARA was not induced, which would suggest that in our study rumen buffering was sufficient for all diets. A possible explanation for the SARA in our study is that cows selected in favor of shorter feed particles and against longer feed particles. Similar sorting behavior was reported by Leonardi et al. (2005) and Bhandari et al. (2007) and shows that the diet consumed can vary substantially from the diet that is offered. The sorting in favor of the feed particles retained by the bottom pan of the PSPS was large, and ranged from 154.5 to 173.5% among diets. The implication of this sorting in favor of the finest feed particles might have been limited, because the fraction of the feed retained by the bottom pan only ranged from 2.2 to 3.0% among diets. On a 24-h basis, the sorting did not affect the intake of feed particles greatly, because only between 5 and 10% of orts were allowed. However, ingestion of small feed particles following feed delivery and a delay in the ingestion of longer feed particles after feed delivery would increase diurnal variation in rumen pH and, thereby, increase the risk of SARA. The daily average rumen pH ranged from 6.21 to 6.27 among diets, whereas the duration of the rumen pH below 5.6 ranged from 120.6 to 197.2 min/d among diets, thereby showing that diurnal variation of rumen pH was substantial.

In our study, reducing the chop lengths of alfalfa silage and oat silage did not affect the pH and VFA in the rumen. Earlier studies also found that the particle length of alfalfa silage, corn silage, and oat silage did

not affect rumen pH and total VFA (Krause and Combs, 2003; Leonardi et al., 2005). However, in contrast Yang and Beauchemin (2006a) found that reducing the chop length of barley silage affected total rumen VFA quadratically, without affecting rumen pH. Results presented here are contrary to those reported by Krause et al. (2002b), who observed that reducing the average particle length of alfalfa silage reduced rumen pH and increased total rumen VFA and to those reported by Kononoff and Heinrichs (2003a), who found that reducing the particle length of alfalfa haylage increased total rumen VFA and quadratically affected rumen pH. A possible explanation for the discrepancy between the data presented here and the studies conducted by Krause et al. (2002b), Kononoff and Heinrichs (2003a), and Yang and Beauchemin (2006a) could be that the dietary particle lengths were shorter in the earlier studies compared with our studies, and that a reduction in particle length has a greater impact on rumen pH in diets with short particle lengths compared with diets with long particle lengths (Mertens, 1997).

The shorter and longer chop length of both silages not only differed in particle size, but also in silage pH and VFA content. Next to feed particle size, silage pH can affect rumen pH (Thomas and Wilkinson, 1975). This effect cannot be quantified using results obtained in earlier studies on the effect of forage particle size in dairy cows, because most of these studies either did not chop silages at different lengths or did not determine silage pH. Yang and Beauchemin (2006a) did chop barley silage at different lengths and determined silage pH, as well as rumen pH. However, because silage pH was not affected by forage chop length in this study, the effect of this pH on rumen conditions could also not be assessed.

A reduction in feed particle size increases the surface area of the particles for microbial attachment, which can increase the ruminal digestion and VFA production. However, a reduction in particle size may not result in increased ruminal digestion and VFA production because of increased particulate passage rate (Soita et al., 2002; Yang and Beauchemin, 2006a). Despite this, several studies with dairy cows have reported that a reduction in forage particle size does affect rumen digestion (Krause et al., 2002a; Yang and Beauchemin, 2006b).

The absence of an effect of forage chop length on the concentrations of acetate, propionate, and butyrate, as well as the acetate to propionate ratio agrees with Leonardi et al. (2005) and Yang and Beauchemin (2006a), who also observed that the particle length of oat silage and barely silage did not affect these VFA concentrations and this ratio. However, Krause et al. (2002a) and Kononoff and Heinrichs (2003a) found that reducing

the particle length of alfalfa silage and alfalfa haylage reduced the acetate to propionate ratio. Comparison of the above studies suggests that studies in which reduction in forage particle size resulted in the greatest depression in rumen pH, also showed the greatest reduction in acetate to propionate ratio. However, comparison of VFA concentrations among studies must be done with caution, because differences in the acidification and processing of rumen fluid after collection and before analysis can affect the loss of VFA and, therefore, affect VFA concentrations, and pH and VFA concentrations vary considerably among different location in the rumen (Duffield et al., 2004).

The lack of an effect of forage chop length on rumen ammonia is in agreement with Kononoff and Heinrichs (2003a) and Leonardi et al. (2005), who found that the particle length of alfalfa hay, alfalfa haylage, and oat silage did not affect rumen ammonia, suggesting that a reduction of forage particle length does not affect the protein digestion and uptake of ammonia by microbes in the rumen (Clark et al., 1992). In contrast, Yang and Beauchemin (2006a) found that rumen ammonia quadratically increased when the particle length of barley silage was decreased. In their study rumen digestion of dietary protein was not affected by forage particle size, but the microbial nitrogen as a percentage of nitrogen intake tended to increase when barley particle size was reduced. This demonstrates that factors other than rumen digestion of protein can affect the ruminal ammonia concentration, which might explain the discrepancies in forage particle length effect on rumen ammonia among studies.

Similar to our study, Kononoff and Heinrichs (2003a) also did not find that reducing the particle length of alfalfa affected the rumen liquid outflow rate, which averaged 16.4%/h across diets. Our findings also agree with Yang and Beauchemin (2006b) who found that reducing the particle length of barely silage did not affect liquid outflow rate from the reticulorumen, which averaged 9.5%/h across diets. In contrast to our study, Krause et al. (2002a) observed that reducing the particle length of alfalfa reduced the rumen liquid outflow rate from 13.8 to 11.8%/h. This reduction was contributed to a reduction in saliva production. The particle lengths of the diets from Krause et al. (2002a) were shorter than those in our study. As such, the physical effective fiber content of all the diets in our study could have been sufficient to fully stimulate chewing and saliva production (Mertens, 1997), which explained why diets did not differ in saliva production and rumen liquid outflow rate. Furthermore, although a reduction in forage particle size reduces chewing (Krause et al., 2002b; Beauchemin et al., 2003; Yang and Beauchemin, 2006b), this might not reduce saliva production (Mae-

kawa et al., 2002; Beauchemin et al., 2003) and liquid rumen outflow rate, due to increased saliva production during resting; that is, in the absence of chewing (Mae-kawa et al., 2002).

The concentrations of glucose, urea, and lactate in blood plasma were similar to those reported by Plaizier (2004), but were lower than those reported by Bhandari et al. (2007), who reported concentrations of glucose, lactate, and urea that ranged between 4.12 and 4.20 mM, 1.02 and 1.33 mM, and 6.07 and 6.96 mM, respectively. These differences between our study and that of Bhandari et al. (2007) might be explained by the greater dietary content of concentrate and CP in the earlier study. The plasma concentrations of glucose and urea were within the normal ranges from 2.4 to 4.2 mM and from 2.8 to 8.8 mM, respectively (Merck, 2006). These results agree with Bhandari et al. (2007), who found that reducing the chop length of alfalfa and corn silage from 19 to 10 mm also did not affect the blood plasma concentrations of glucose, urea, and lactate. Plaizier (2004) found that reducing the dietary particle length by replacing alfalfa silage with chopped hay increased blood glucose and decreased blood urea, but this was due to differences among these forages other than particle length.

Similar to our study, Krause et al. (2002a), Kononoff and Heinrichs (2003a), and Yang and Beauchemin (2006b) did not find that the particle lengths of alfalfa silage and barley silage affected milk yield. However, in contrast Leonardi et al. (2005) found that reducing the particle length of oat silage increased milk yield. Our results also agree with Krause et al. (2002a), Kononoff and Heinrichs (2003a), Leonardi et al. (2005), and Yang and Beauchemin (2006b), who also found that the particle lengths of alfalfa silage, barley silage, and oat silage did not affect milk fat percentage. Because rumen pH can affect milk fat percentage (Mertens, 1997; Griinari et al., 1998), the absence of a forage chop length effect on rumen pH will have contributed to the absence of this chop length effect on milk fat percentage. Mertens (1997) showed that milk fat percentage is more sensitive to differences in forage particle size when the percentage is low compared with when it is high. The fact that, despite the low milk fat percentages, forage chop length did not affect milk fat percentage might have been due the limited range of forage particle length, as well as due to the very limited differences in rumen pH and chemical composition among diets. Despite of an absence of an effect on milk fat percentage, our study showed that reducing the particle length of oat silage tended to increase milk fat yield. The increase in milk fat yield could be the result of an increase in DMI that occurred when the chop length of oat silage was reduced. A reduction in forage particle size can

reduce milk fat, if it reduces rumen pH, possibly through the increase in *trans* fatty acids in the rumen, or decreases the supply of acetate and butyrate (Mertens, 1997; Griinari et al., 1998). Because none of these were affected by reducing the chop lengths of alfalfa silage and oat silage, the absence of an effect on milk fat percentage was not unexpected.

The absence of a forage particle length effect on milk protein percentage agrees with Krause et al. (2002a), Leonardi et al. (2005), and Bhandari et al. (2007). However, in contrast to our study, Kononoff and Heinrichs (2003a) found a quadratic effect of the particle length of alfalfa silage on milk protein percentage, but not on milk protein yield. Also, Leonardi et al. (2005) found that reduced particle length of oat silage increased milk true protein yield, whereas Yang and Beauchemin (2006b) found that reducing the particle length of barley silage increased milk protein percentage without affecting milk protein yield. The discrepancy between the studies from Kononoff and Heinrichs (2003a) and our study might be related to the relatively low milk protein percentages in the earlier study, which ranged from 2.82 to 2.93% among diets. Although Leonardi et al. (2005) reported true protein and nontotal protein, their values for true protein in milk also suggest that their concentrations of milk protein were much lower than those in our study. The lower milk protein percentages in the studies from Kononoff and Heinrichs (2003a) and Leonardi et al. (2005) could imply that in the earlier studies milk protein was constrained by other factors than in our study, which may explain discrepancies among these studies.

CONCLUSIONS

Reducing the chop length of alfalfa and oat silage harvested using a New Holland forage harvester (model 790) from 19 to 6 mm reduced the geometric mean particle length from 14.2 to 10.9 and from 13.4 to 10.4 mm, respectively. Incorporation of either 24% of DM longer chop or shorter chop alfalfa silage and either 24% of DM longer chop or shorter chop oat silage in TMR of lactating dairy cows that contained 52% of DM of barley grain-based concentrate showed that reducing the alfalfa chop length did not affect feed intake, whereas reducing the oat silage chop length increased DMI from 19.4 to 21.2 kg/d. Reducing the chop lengths of alfalfa silage and oat silage chop length did not affect milk production, rumen fermentation, feeding behavior, meal patterns, or blood metabolites. Milk fat percentage was lower than milk protein percentage for all diets, suggesting that these diets induced SARA. This suggestion was supported by the rumen pH, which was lower than 5.6 for more than 120 min/d for all diets.

The particle size distribution of the all diets did not suggest that cows were at risk for SARA. Despite this, SARA might have occurred due to the sorting against long feed particles in favor of short feed particles.

ACKNOWLEDGMENTS

The staff of the Glenlea Research Station, University of Manitoba, Terri Garner, and Janice Haines are thanked for their technical assistance. This study was supported by grants from Dairy Farmers of Canada (DFC), the Agri-Food Development Research Initiative (ARDI), and the Natural Sciences and Engineering Research Council of Canada (NSERC).

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