Effect of Different Dietary Geometric Mean Particle Length and Particle Size Distribution of Oat Silage on Feeding Behavior and Productive Performance of Dairy Cattle

C. Leonardi,¹ K. J. Shinnars,² and L. E. Armentano¹

¹Department of Dairy Science and

²Department of Biological Systems Engineering, University of Wisconsin, Madison 53706

ABSTRACT

Twenty lactating Holstein cows (5 primiparous and 15 multiparous) were used in a 5×5 Latin Square design, with 5 treatments and 3 periods of 21 d each. Diets contained 25% corn silage, 25% oat silage, and 50% concentrate (dry matter basis). The 5 treatments tested in the experiment were long oat silage (LOS), medium oat silage (MOS), fine from long oat silage (FLOS), fine from medium oat silage (FMOS), and half LOS plus half FLOS (LFLOS). The geometric mean particle length (GMPL) of the diets was 6.68, 5.19, 4.46, 4.35, and 5.39 mm for LOS, MOS, FLOS, FMOS, and LFLOS, respectively. The LFLOS was designed to provide dietary GMPL similar to MOS, but with a more bimodal particle size distribution (PSD). Linear and quadratic effects of GMPL were tested, based on the mean GMPL of the feed actually consumed (cGMPL). Contrasts were used to test for the effect of different PSD (MOS vs. LFLOS) and to test for differences between FMOS and FLOS, which would indicate unequal fermentations in the MOS and LOS silos. No differences were detected between FMOS and FLOS in most of the variables measured. Increasing cGMPL linearly decreased dry matter intake, milk production, and milk protein percentage and yield without affecting milk fat percentage, milk fat yield, ruminal pH, and ruminal volatile fatty acid concentration. Although cows fed diets with increasing cGMPL spent more time eating and chewing per day and per kilogram of dry matter intake, there was no effect of cGMPL on rumen pH. Feeding medium oat silage increased milk fat percentage and yield compared with feeding a mixture of long and fine oat silage.

(Key words: oat silage, particle size distribution, geometric mean particle length)

Abbreviation key: cGMPL = geometric mean particle length of the diet consumed; dGMPL = dietary geometric mean particle length; FLOS = fine from long oat silage; FMOS = fine from medium oat silage; GMPL = geometric mean particle length; LFLOS = 50% long oat silage and 50% fine from long oat silage; LOS = long oat silage; MF = multiparous, fistulated; MOS = medium oat silage; NDFI = neutral detergent fiber intake; peNDF = physically effective neutral detergent fiber; PSD = particle size distribution.

INTRODUCTION

To maintain rumen fermentation and cow health, NRC (2001) recommends feeding dairy cattle a minimum of 25% dietary NDF. To ensure a minimum amount of NDF with an adequate physical structure to stimulate chewing activity, a minimum of 19% dietary forage NDF also has been recommended (NRC, 2001). However, forage particle length can vary extremely, and it is not clear what measurement of a forage physical characteristic would best predict the animal response.

Two terms have been introduced to distinguish between the ability of a feed to stimulate chewing activity and its ability to maintain milk fat percentage: effective NDF and physically effective NDF (peNDF; Mertens, 1997). Effective NDF is defined as the capability of the NDF of a feed to replace forage NDF in maintaining milk fat percentage. Physically effective NDF is defined as feed NDF that stimulates chewing and is therefore related to feed particle size (Mertens, 1997). The concept of peNDF has been introduced to unify into a single measurement the NDF concentration and the physical characteristics of a feed. One practical system developed to measure feed peNDF multiplies NDF concentration by the material retained on a sieve with an aperture of 1.18 mm (Mertens, 1997). The intake of peNDF calculated as described by Mertens (1997) has been significantly correlated with total time spent chewing ($r = 0.52$; Beauchemin et al., 2003). However, forages with a similar percentage of material retained above a screen of 1.18 mm can

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Corresponding author: L. E. Armentano; e-mail: learment@wisc.edu.

be chopped at different lengths. Forages with equal amounts of material above the 1.18-mm screen can have much different geometrical mean particle length (**GMPL**) because of the presence of differing proportions of very long and intermediate length particles. It is possible that GMPL will accurately predict the physical effectiveness of the diet across these different particle size distributions (**PSD**). The GMPL can be calculated with a portable system comprising 3 screens and a pan (ANSI, 2001) or by a laboratory device comprising 5 screens and a pan (ANSI, 1998). Analyses of the former are commercially available from Cumberland Valley Analytical Services (Hagerstown, MD) and UW Soil & Forage Analysis Laboratory (Marshfield, WI) and for the latter are commercially available from Dairyland Laboratories, Inc. (Arcadia, WI). It is also possible that simply stating the mass above a certain screen, which is easier to measure than GMPL, would describe physical effectiveness but that a screen >1.18 mm may be most useful. A third possibility is that introducing more long particles increases physical effectiveness more than can be accounted for by increasing GMPL. The primary objective of this study was to address whether GMPL alone accurately predicted the physical effectiveness of a mixed ration fed to lactating dairy cattle without considering PSD. Because GMPL and the fraction above certain screens are generally highly confounded, we purposely manipulated the oat-lage content of 2 of our diets to provide similar GMPL with differing PSD. In addition, oat silage was processed to various lengths to quantify the response of lactating cows across a range of particle sizes derived from forage.

MATERIALS AND METHODS

Animals

Fifteen multiparous and 5 primiparous lactating Holstein cows were assigned to a replicated 5 × 5 Latin Square design, with periods of 21 d. The trial lasted only 3 periods of the 5 planned. Eight multiparous cows were ruminally fistulated. One square consisted of multiparous, fistulated (**MF**) cows with the highest milk production among the previously fistulated cows assigned to the experiment. A second square consisted of multiparous cows with the highest milk production among nonfistulated multiparous cows. A third square consisted of the remaining multiparous cows, including the 3 fistulated cows not included in the MF group. A fourth square consisted of primiparous cows. At the beginning of the study, MF cows averaged 62 ± 9 (average ± SD) DIM and produced 51.6 ± 2.4 kg of milk daily, the square of multiparous cows with the highest milk production averaged 58 ± 28 DIM and produced

Table 1. Ration composition.

Ingredient	Diet ¹		
	FMOS + MOS	LFLOS	FLOS + LOS
	(g/100 g of DM)		
Long oat silage	—	12.6	25.1
Medium oat silage	25.1	12.5	—
Corn silage	25.1	25.1	25.1
Corn grain ground	27.2	27.2	27.2
Roasted soybeans	9.6	9.6	9.6
Soybean meal, 48% CP	9.2	9.2	9.2
Blood meal	0.8	0.8	0.8
Tallow	0.8	0.8	0.8
Calcium carbonate	1.0	1.0	1.0
Dicalcium phosphate	0.4	0.4	0.4
Trace mineral salt ²	0.5	0.5	0.5
Vitamin mix ³	0.3	0.3	0.3

¹FMOS = Fine from medium oat silage, MOS = medium oat silage, FLOS = fine from long oat silage, LFLOS = 50% long oat silage and 50% fine from long oat silage, and LOS = long oat silage.

²Contained 0.55% Mn, 0.55% Zn, 0.35% Fe, 0.14% Cu, 0.008% I, 0.006% Se, and 0.002% Co.

³Contained 3304 IU/g of vitamin A, 1101 IU/g of vitamin D, and 11 IU/g of vitamin E.

48.6 ± 1.7 kg of milk daily, the square of multiparous cows with the lowest milk production averaged 56 ± 31 DIM and produced 39.9 ± 4.2 kg of milk daily, and the square of primiparous cows averaged 65 ± 28 DIM and produced 33.1 ± 1.9 kg of milk daily. The sequence of treatments was selected to balance for residual effects. Cows were housed and fed individually in a tie-stall and stanchion barn and had free-choice access to water. The Animal Care Committee of the College of Agricultural and Life Sciences of the University of Wisconsin-Madison approved all animal procedures.

Diets

Diets were mixed once daily and fed for ad libitum intake twice daily at 1100 and 1600 h. The amount of feed offered was adjusted daily to obtain approximately 10 to 15% orts (as-fed basis). Cows were allowed to exercise daily from 0800 until 1100 h and had access to feed for approximately 19 h/d. Diets were formulated to be isonitrogenous and isoenergetic and to have similar NDF concentrations. All diets contained 25.1% corn silage, 25.1% oat silage, and 49.8% concentrate (DM basis, Table 1) and had similar chemical composition, which was mathematically calculated from individual feedstuff analytical values (Table 2). Small differences in diets' chemical composition were due to unequal chemical composition of oat silages (Table 2). Treatment differences were due to oat silage having either different GMPL or PSD. Treatments consisted of long oat silage (**LOS**), medium oat silage (**MOS**),

Table 2. Chemical composition of forages and diets.

Item	Forage ¹			Diet ²	
	Long OS	Medium OS	CS	FMOS + MOS	FLOS + LFLOS + LOS
DM, g/100g (as fed)	30.2	28.5	36.0	47.3	48.5
	(g/100 g of DM)				
CP	14.5	14.0	8.2	18.0	18.2
NDF	53.3	54.9	33.8	26.2	25.8
ADF	36.8	38.0	22.3	17.4	17.1
NFC ³	20.2	19.1	50.7	42.5	42.7
Fatty acid ⁴	1.4	1.3	2.7	6.3	6.3
Ash ⁵	10.6	10.7	4.6	7.0	7.0

¹OS = Oat silage; CS = corn silage.

²FMOS = Fine from medium oat silage, MOS = medium oat silage, FLOS = fine from long oat silage, LFLOS = 50% long oat silage and 50% fine from long oat silage, and LOS = long oat silage. NE_L concentration was 1.66 Mcal/kg of DM for all diets and was calculated based on NRC (2001) values for individual feedstuffs.

³NFC = 100 – (fatty acid + 1 + NDF + CP + ash).

⁴Fatty acid represented the sum of C₁₄ to C₁₈.

⁵Diets contained 0.77% Ca and 0.43% P.

fine rechopped long oat silage (**FLOS**), fine rechopped medium oat silage (**FMOS**), and half LOS plus half FLOS oat silage (**LFLOS**). Oat silage and not alfalfa silage was used in this experiment to obtain a more uniform particle size distribution. Oats have the characteristic of having one culm and therefore less branching than alfalfa if harvested before heading, which was hypothesized to produce a more homogeneous product from chopping. The GMPL of diets offered (**dGMPL**) was 6.68, 5.19, 4.46, 4.35, and 5.39 mm for LOS, MOS, FLOS, FMOS, and LFLOS, respectively (Figure 1). Long and MOS were obtained directly from the field. Oats were cut in the morning and wilted in rows for 24 h. The following afternoon, every other row was chopped with a conventional forage harvester (Gehl-850; Gehl Co., West Bend, WI) equipped with 8 knives and the 15-teeth feed roll drive sprocket for the medium length. The long material was obtained from the remaining rows with the same machine but with only 2 knives and the 21-teeth feed roll drive sprocket. Long and MOS were stored in 2 separate 2.4-m diameter silo bags. The 2 fine oat silages (FMOS and FLOS) were obtained daily just before feeding by rechopping the LOS and MOS. This further size reduction was done with a stationary recutter/blower (Gehl FB-88; Gehl Co.) equipped with a 7.6-cm nominal size openings screen. A buffered acid preservative (Ultra CURB; Kemin, Des Moines, IA) containing 82% total acids, which included propionic, acetic, benzoic, and sorbic acid, was applied during and after ensiling at 1.8 kg/tonne of fresh material to reduce spoilage. The combination of low DM content, a hot and humid summer, and low feeding rate favored spoiling during the second period (June). Therefore, to feed unspoiled material,

significant amounts of silage were discarded, leaving adequate oat silage to complete only 3 periods of the 5 planned. Corn silage was also rechopped daily utilizing the same recutter and screen previously described for the oat silage. Corn silage was rechopped to minimize its effect on GMPL and PDS.

Feed Sampling and Analysis

Diets were adjusted weekly to account for forage DM fluctuation. Feed samples were collected once during the last week of each experimental period, dried at 60°C for 48 h, ground to pass through a 1-mm screen (Wiley Mill; Arthur H. Thomas, Philadelphia, PA), and analyzed for DM, OM, CP, NDF, ADF, and fatty acid. Orts were sampled during the last 5 d of each period and composited by animal proportionally to the weight of feed refused each day. The composite ort samples were dried at 60°C for 48 h and analyzed for DM and NDF. Samples of Orts and diets were collected for PSD determination on d 7 and 21 of each period to determine feed sorting. Particle size distribution of forages, diets, and Orts was determined by sieving samples using the Wisconsin Particle Size Separator in accordance with the ASAE Standard S424.1 protocol (ANSI, 1998). Geometric mean particle length was calculated assuming a mean length of 48 mm for the material retained on the top screen of the separator, which has 5 square-hole screens. In descending order from the top screen, the diagonal openings are 26.9, 18, 8.98, 5.61, and 1.65 mm and a pan.

The analytical DM was determined by oven drying at 100°C for 24 h, and OM was determined by ashing at 550°C for 12 h. Crude protein content was deter-

Figure 1. Dietary particles retained on each screen (as-fed basis). Screens are labeled from left (long material) to right (fine material) as 26.9, 18, 8.98, 5.61, and 1.65 mm and pan, respectively. Diets consisted of fine from medium oat silage (FMOS), fine from long oat silage (FLOS), medium oat silage (MOS), 50% long oat silage and 50% fine from long oat silage (LFLOS), and long oat silage (LOS). Standard deviations for 26.9, 18, 8.98, 5.61, and 1.65 mm and pan were 0.2, 1.0, 1.7, 0.9, 1.1, and 1.7 for FMOS; 0.4, 1.3, 2.4, 1.0, 1.3, and 3.5 for FLOS; 1.9, 0.7, 1.3, 1.4, 0.9, and 1.7 for MOS; 1.4, 0.8, 1.5, 1.4, 1.1, and 2.5 for LFLOS; and 5.2, 1.7, 1.6, 1.3, 1.5, and 3.2 for LOS.

mined by microKjeldahl analysis (AOAC, 1990). Neutral detergent fiber was determined using α -amylase (FAA, Ankom Technology, Fairport, NY), and sodium sulfite was corrected for ash concentration according to Van Soest et al. (1991), adapted for Ankom²⁰⁰ Fiber Analyzer (Ankom Technology). Acid detergent fiber was determined using the method described by Goering and Van Soest (1970), adapted for Ankom²⁰⁰ Fiber Analyzer (Ankom Technology) and corrected for ash concentration. Fatty acids were determined by following the procedure described by Sukhija and Palmquist (1988) and represented the sum of C₁₄ to C₁₈. The NFC component was calculated as 100 – (NDF + ether extract + CP + ash), where ether extract was calculated as fatty acid plus one (NRC, 2001). Reported NFC values are not corrected for NDF-CP or NPN.

Sampling

Cows were milked twice daily. Milk production was recorded, and milk was sampled at each milking during the last 5 d of each period. Milk samples were analyzed for protein and fat by infrared analysis (Ag-Source Milk Analysis Laboratory, Menomonie, WI) with a Fossmatic-605 (Foss Electric, Hillerød, Denmark) according to AOAC (1990).

On d 19 and 20 of each period, rumen fluid from cows in square MF was collected for 24 h, every 4 h, starting immediately before feeding. Samples were taken from 4 different locations in the rumen with a metal filter probe. Rumen pH was determined immediately after the sample was collected (Twin pH-meter model B-123; Spectrum Technologies Inc., Plainfield, IL). One milliliter of rumen fluid was mixed with 20 μ L of 50% trichloroacetic acid and frozen until analysis for NH₃ (Chaney and Marbach, 1962). Another milliliter of rumen fluid was acidified with 20 μ L of 50% H₂SO₄ and frozen until analysis for VFA as described by Bal et al. (2000).

On d 19 of each period, 6 sets of 4 Dacron polyester bags (9 × 15 cm; 52 ± 5 μ m pore size) were incubated for 24 h in each cow of square MF to determine ruminal in situ DM and NDF disappearance of unground soybean hulls. To account for possible effects of initial ruminal pH on NDF degradability, the starting time of each set was staggered every 4 h, with the first set being incubated right before feeding. Bags containing 5 ± 0.25 g of DM were soaked in warm water for 5 min before incubation, placed in a nylon laundry bag, and inserted in the ventral sac of the rumen. After incubation, bags were rinsed immediately in cold water and washed in a commercial washing machine for one cycle

of 15 min. Bags were dried in a forced-air oven at 60°C for 48 h to determine DM disappearance. Residues from quadruplicate bags were composited and analyzed for NDF.

Feeding behavior was monitored visually for 24 h during the last day of each experimental period. Cows were monitored during the exercise period but were not observed during milking time. Individual cow's eating and ruminating activities were recorded every 5 min. It was assumed that each activity persisted for the entire 5-min interval. Chewing time represented the sum of the time spent eating and ruminating. The time spent eating, ruminating, and chewing expressed per kg of DMI was calculated utilizing the average DMI measured during the last 5 d of each experimental period.

Liquid and Cr-mordanted straw passage rates were estimated for 2 squares of cows (MF and square of multiparous cows with lowest milk production). Lithium-Co-EDTA and Cr-mordanted fiber were prepared as described by Udén et al. (1980). Chromium-mordanted fiber was prepared utilizing wheat straw NDF ground through a 6-mm screen (Wiley Mill; Arthur H. Thomas). In 2 nonruminally fistulated cows, lithium-Co-EDTA was orally bolused, and Cr-mordanted fiber was fed. It was not possible to bolus Cr-mordanted fiber because of the excessive volume. Chromium-mordanted fiber was top-dressed on the fresh diet as soon as the cows were fed. Ingestion within 2 min was confirmed visually, and there did not appear to be any residual marked straw. In the remaining 8 cows, markers were placed into the rumen through the rumen fistula at morning feeding and not mixed with the rumen content. Fecal grab samples were collected at 0, 6, 12, 18, 24, 36, 48, 60, 72, and 96 h after dosing to determine solid and liquid rate of passage. Samples were dried, and fecal marker concentrations of Cr and Co were determined by direct current plasma emission spectroscopy (Spectra Metrics, Inc., subsidiary of Beckman Instruments, Inc., Andover, MA), as described by Combs and Satter (1992).

Calculations and Statistical Analysis

Sorting was calculated as the actual intake of each screen expressed as a percentage of the predicted intake. Predicted intake for an individual screen was calculated as the as-fed intake for the total diet multiplied by the as-fed fraction of that screen in the diet offered. Values equal to 100% indicate no sorting, <100% show selective refusals, and >100% indicate preferential consumption.

Data were analyzed using the mixed procedure of SAS (1998). Four individual degree of freedom con-

trasts were made. Polynomial effects of GMPL were tested (linear and quadratic). Contrast coefficients were calculated utilizing the average GMPL of diets consumed (**cGMPL**) and not dGMPL. The cGMPL values used to calculate contrast coefficients were treatment means ($n = 5$). Contrasts were built to test for the effect of different PSD (MOS vs. LFLOS) and to test for differences between FMOS and FLOS. Diets FMOS and FLOS had similar dGMPL; therefore, differences between these 2 diets would indicate unequal silage fermentation caused by ensiling forage with different particle length. This comparison allowed us to discern whether differences caused by either GMPL or PSD were direct effects of particle length and distribution on the cows or if these effects were confounded by an indirect effect caused by different silage fermentation patterns.

Daily DMI, milk production, milk composition, chewing activities ($n = 60$), and Cr-mordanted straw and liquid rates of passage ($n = 30$) were analyzed, with the final model including square, period, and treatment as fixed effects and cow within square as a random effect. The interactions square $\times$ treatment, period $\times$ treatment, and square $\times$ period were not significant ($P > 0.25$) and thus were not included in the final model.

Sorting ($n = 116$) was analyzed by day as repeated measurements, utilizing a first-order autoregressive covariance structure. The final model included square, period, day, treatment, treatment $\times$ day, square $\times$ treatment, period $\times$ treatment, and square $\times$ period as fixed effects. Terms specified for the random statement were cow within square and treatment $\times$ period $\times$ cow within square.

Ruminal pH, VFA, and NH_3 ($n = 175$) were analyzed by day and hour as repeated measurements, utilizing a first-order autoregressive covariance structure for hour and compound symmetry for day. The final model included period, day, hour, treatment, and hour $\times$ treatment as fixed effects. The interactions treatment $\times$ day and day $\times$ hour were not significant ($P > 0.25$) and thus were not included in the final model. Terms specified for the random statement were cow, treatment $\times$ period $\times$ cow, and day $\times$ treatment $\times$ period $\times$ cow.

Dry matter and NDF degradability of in situ bags ($n = 85$) were analyzed by hour as repeated measurements, utilizing a first-order autoregressive covariance structure. The final model included period, hour, and treatment as fixed effects. The interaction of treatment $\times$ hour was not significant ($P > 0.25$) and thus was not included in the final model. Terms specified for the random statement were cow and treatment $\times$ period $\times$ cow. All covariance structures just listed

provided the model with the best fit according to the Schwarz Bayesian criterion. Values reported are least squares means. Significance was declared at $P \leq 0.05$, and a trend was reported if $0.05 < P \leq 0.10$.

When cGMPL had a significant linear effect on the response variable, regression equations were determined utilizing Proc REG (SAS Inst., Inc., Cary, NC). Equations were obtained regressing least squares means of dependent variables against cGMPL treatment means ($n = 5$).

To verify the effect of sorting on the capability of GMPL to predict animal response, the linear effect of dGMPL or cGMPL was tested on dependent variables. Data were analyzed utilizing the mixed procedure of SAS (1998). The dependent variables considered were DMI, milk production, milk protein yield, and time spent eating and ruminating both as min/d and min/kg of DMI. The model included period, square, either dGMPL or cGMPL ($df = 1$), and cow within square as a random variable. The statistical models were the same for cGMPL vs. dGMPL except for the inclusion of either term. Therefore, to determine which model better explained the dependent variables variance, fit statistics (Akaike's information criterion), residual estimate, and significance of dGMPL and cGMPL were compared.

RESULTS AND DISCUSSION

One objective of this experiment was to differentiate the physical effect of feeding diets with different GMPL from a combination of physical and chemical effects. Differences between FMOS and FLOS would indicate that medium and LOS fermented differently. Very small but statistically significant differences were detected between FMOS and FLOS for sorting of 18-mm ($P = 0.02$) and 8.98-mm ($P = 0.004$) screens. Cows fed FLOS ate 98.1% of the offered particles retained on 18-mm screen, and 98.6% of the offered particles retained on 8.98-mm screen; conversely, cows fed FMOS ate 101.3% of the offered particles retained on 18-mm screen and 100.7% of the offered particles retained on 8.98-mm screen (Table 3 and Figure 2). No other significant differences between FMOS and FLOS were detected. Therefore, it was concluded that changes caused by GMPL and PDS are uniquely due to physical characteristics and not different chemical characteristics attributable to altered silage fermentation.

Forage and Diet Characteristics

Long and MOS had similar chemical compositions (Table 2). Both oat silages were wetter than expected.

Table 3. Effect of different geometric mean particle length (GMPL), particle size distribution (PSD), and silo on sorting activity.

Statistical contrast ¹	Square hole diagonal opening, mm					
	26.9	18	8.98	5.61	1.65	Pan
	(P)					
GMPL						
Linear	0.10	0.0002	0.10	0.0007	<0.0001	<0.0001
Quadratic	0.98	0.17	0.09	0.85	0.20	0.30
PSD	0.19	0.39	0.12	0.001	0.27	0.50
Silo	0.23	0.02	0.004	0.93	0.23	0.68

¹Statistical contrast: linear and quadratic effects of different GMPL; effect of different PSD but similar GMPL (MOS vs. LFLOS = medium oat silage vs. 50% long oat silage and 50% fine from long oat silage); effect of silo fermentation characteristics but similar GMPL (FMOS vs. FLOS = fine from medium oat silage vs. fine from long oat silage).

Long oat silage was slightly dryer and was 1.6 percentage units lower in NDF than MOS. Therefore, FLOS, LFLOS, and LOS had a slightly lower NDF concentration compared with FMOS and MOS (Table 2).

As expected, LOS had more material retained on 26.9- and 18-mm screens than the remaining diets (Figure 1). Diet LFLOS was a mixture of equal parts of FLOS and LOS; therefore, LFLOS had more material retained on 26.9-, 18-, and 1.65-mm screens and in the pan but less material retained on 8.98- and 5.61-mm screens than MOS (Figure 1). Consequently, MOS and LFLOS had different PSD, but similar dGMPL (5.19 vs. 5.39 mm, respectively), as intended. Also, FMOS and FLOS had similar dGMPL (4.35 vs. 4.46 mm, respectively). The cGMPL was 6.25, 5.05, 4.39, 4.32, and 5.18 mm for LOS, MOS, FLOS, FMOS, and LFLOS, respectively.

Intakes and Sorting

Increasing cGMPL linearly decreased DMI ($P = 0.002$, Table 4) and NDF intake (NDFI, $P = 0.002$). Cows decreased DMI by 0.9 kg/d for each 1-mm increment in cGMPL. Various studies have been conducted testing the effect of different forage lengths on DMI. The results to this point have been contradictory. Krause et al. (2002a) and some earlier studies (Shaver et al., 1986; Woodford et al., 1986) reported no significant effect of forage particle size on DMI. Fisher et al. (1994) found that increasing alfalfa silage mean particle length from 3.02 to 9.57 mm decreased DMI of multiparous cows by 1.1 kg/d. Mooney and Allen (1997) also reported decreased DMI of 1.7 kg/d by feeding alfalfa silage with increasing mean particle size (5.8 vs. 11.4 mm) for diets containing whole, linted cottonseed.

Dietary characteristics such as NDF and starch concentrations and starch fermentability may affect ani-

Figure 2. Least squares means for sorting activity [$100 \times (\text{screen i intake}/\text{screen i predicted intake})$] (as-fed basis) of cows fed diets containing forages with different geometric mean particle length, different particle size distribution, and from different silo. Diets consisted of fine from medium oat silage (FMOS), fine from long oat silage (FLOS), medium oat silage (MOS), 50% long oat silage and 50% fine from long oat silage (LFLOS), and long oat silage (LOS). Screens are labeled from left (long material) to right (fine material) as 26.9, 18, 8.98, 5.61, and 1.65 mm and pan, respectively.

mal response to feeding different dietary particle length and may explain the variability across experiments. Krause and Combs (2003) tested this hypothesis by feeding diets with different GMPL at 2 dietary starch concentrations and utilizing starch sources

with different fermentability. Dietary NDF concentration was kept relatively constant across diets. Increasing dietary GMPL from 2.6 to 3.8 mm consistently increased DMI at various starch levels and starch fermentabilities, and no significant interactions were de-

Table 4. Effect of different geometric mean particle length (GMPL), particle size distribution (PSD), and silo on DMI, NDF intake (NDFI), milk yield, and milk composition.

	Diet ¹					SEM	Statistical contrast (<i>P</i>) ²			
	FMOS	FLOS	MOS	LFLOS	LOS		Linear	Quadratic	PSD	Silo
DMI, kg/d	22.1	22.0	21.7	21.1	20.4	0.5	0.002	0.97	0.30	0.92
NDFI	5.7	5.5	5.4	5.3	5.1	0.2	0.002	0.56	0.43	0.31
Milk yield, kg/d	39.6	40.2	38.8	38.9	38.2	1.0	0.004	0.45	0.80	0.34
Milk composition, %										
True protein	2.73	2.71	2.73	2.71	2.69	0.05	0.14	0.51	0.51	0.49
Fat	3.27	3.36	3.42	3.23	3.41	0.11	0.31	0.69	0.05	0.37
Milk component yield, g/d										
True protein	1074	1085	1052	1051	1021	27	0.002	0.79	0.95	0.58
Fat	1287	1344	1318	1250	1280	42	0.19	0.49	0.05	0.11

¹FMOS = Fine from medium oat silage, FLOS = fine from long oat silage, MOS = medium oat silage, LFLOS = 50% long oat silage and 50% fine from long oat silage, and LOS = long oat silage.

²Statistical contrast: linear and quadratic effects of different GMPL; effect of different PSD but similar GMPL (MOS vs. LFLOS); effect of silo fermentation characteristics but similar GMPL (FMOS vs. FLOS).

Figure 3. Effect of different geometric mean particle length, particle size distribution, and silo on ruminal pH diurnal fluctuations. Diets consisted of fine from medium oat silage [FMOS (●)], fine from long oat silage [FLOS (○)], medium oat silage [MOS (■)], 50% long oat silage and 50% fine from long oat silage [LFLOS (□)], and long oat silage [LOS (▲)]. Pooled SEM = 0.13. Significant treatment $\times$ time interaction ($P = 0.04$).

tected (Krause and Combs, 2003). One difference between Krause and Combs (2003), where increasing GMPL increased DMI, and Krause et al. (2002a and b), where no differences in DMI were observed, was time ruminal pH below 5.8. In Krause and Combs (2003) starch intake was higher, and consequently time ruminal pH <5.8 was greater than in Krause et al. (2002a, b); as suggested by the authors, this could increase the likelihood of a negative effect of decreasing forage particle size. In the present experiment, dGMPL range (3.35 to 6.68 mm) and rumen pH were greater than Krause and Combs (2003) and Krause et al. (2002a and b), and rumen pH was never <5.8 (Figure 3). Therefore, it appears that at a lower rumen pH, long dietary particles can have a positive effect on DMI, whereas at a higher rumen pH, long dietary particles may reduce DMI.

Increasing cGMPL linearly decreased NDFI ($P = 0.002$). This was mainly a result of a lower DMI. However, not all of the decrease in NDFI could be explained by the decrease in DMI. In fact, when DMI was introduced into the model as a covariate, the linear effect of cGMPL on NDFI was still significant ($P = 0.03$; data not shown). The residual linear effect of cGMPL on NDFI could be explained by variation in sorting across diets (Figure 2; Table 3). Feeding diets with increasing GMPL tended to linearly increase sorting against long particles (26.9-mm screen, $P = 0.10$) in favor of smaller particles (1.65-mm screen and pan, $P < 0.001$). Similarly, Leonardi and Armentano (2003) reported that cows generally tend to sort against longer particles in favor of smaller particles. However, in the present experiment, the extent of sorting was smaller, proba-

bly because 50% of dietary DM consisted of silage, whereas in Leonardi and Armentano (2003) the maximum amount of silage fed was 20% of the diet (DM basis). Diets containing only alfalfa hay (40% of dietary DM) as a forage source were more prone to be sorted than diets containing a mixture of alfalfa hay and silage (Leonardi and Armentano, 2003). Sorting affected the NDF concentration of the diet ingested. The NDF concentration of the diet offered was 26.2% for FMOS and MOS and 25.8% for FLOS, LFLOS, and LOS. The NDF concentration of the diet ingested $100 \times (\text{NDFI/DMI})$ was 25.6% for FMOS, 25.0% for FLOS, 24.9% for MOS, 24.9% for LFLOS, and 24.7% for LOS.

There was a significant square $\times$ treatment interaction on sorting of 5.61-mm screen ($P = 0.05$) and of 1.65-mm screen ($P = 0.006$). When fed MOS, LFLOS, and LOS, primiparous cows sorted to a higher extent in favor of particles retained on 1.65-mm screen than did multiparous cows (data not shown). When fed LFLOS, primiparous cows sorted to a higher extent in favor of particles retained on 5.61-mm screen than did multiparous cows (data not shown). Furthermore, square had a significant effect on sorting of particles retained on 26.9-mm screen ($P = 0.04$), 18-mm screen ($P = 0.02$), 8.98-mm screen ($P = 0.02$), and 1.65-mm screen ($P < 0.001$). The difference among squares was attributable mainly to primiparous cows sorting more against longer particles (26.9-, 18-, and 8.98-mm screens) and more in favor of shorter particles (1.65-mm screen) than multiparous cows. Although a statistical comparison was not made, sorting activity across the 3 squares containing only multiparous cows was similar. Intake of particles retained on 26.9-mm screen expressed as a percentage of offered was 80% for primiparous and 94.4% for multiparous cows. Intake of particles retained on 18-mm screen expressed as a percentage of offered was 94.7% for primiparous and 98.4% for multiparous cows. Intake of particles retained on 8.98-mm screen expressed as a percentage of offered was 98.1% for primiparous and 99.6% for multiparous cows. Intake of particles retained on 1.65-mm screen expressed as a percentage of offered was 104.5% for primiparous and 102.4% for multiparous cows. In a previously conducted experiment, sorting activity was not significantly different between primiparous and multiparous cows (Leonardi and Armentano, 2003). Furthermore, treatment effect did not vary between parities (Leonardi and Armentano, 2003). In Leonardi and Armentano (2003), diets contained either only alfalfa hay or a mixture of alfalfa silage and hay. Conversely, in the present experiment, a mixture of corn silage and oat silage was fed. It is possible that the different type of forages fed could

Table 5. Effect of different geometric mean particle length (GMPL), particle size distribution (PSD), and silo on feeding behavior.

Item	Diet ¹					SEM	Statistical contrast (<i>P</i>) ²			
	FMOS	FLOS	MOS	LFLOS	LOS		Linear	Quadratic	PSD	Silo
	(min/d)						<i>P</i>			
Eating	229	236	242	262	267	14	0.02	0.59	0.24	0.66
Ruminating	529	530	539	542	549	14	0.12	0.78	0.60	0.99
Chewing	758	766	779	807	817	20	0.003	0.49	0.17	0.68
	(min/kg of DMI)						<i>P</i>			
Eating	10.6	11.0	11.2	12.7	13.4	0.7	0.001	0.79	0.09	0.60
Ruminating	24.9	24.7	25.7	26.5	28.0	0.9	0.0002	0.96	0.38	0.84
Chewing	35.3	35.7	36.8	39.3	41.5	1.2	<0.0001	0.85	0.08	0.79

¹FMOS = Fine from medium oat silage, FLOS = fine from long oat silage, MOS = medium oat silage, LFLOS = 50% long oat silage and 50% fine from long oat silage, and LOS = long oat silage.

²Statistical contrast: linear and quadratic effects of different GMPL; effect of different PSD but similar GMPL (MOS vs. LFLOS); effect of silo fermentation characteristics but similar GMPL (FMOS vs. FLOS).

account for the different parities effect in the 2 experiments.

In the present experiment, we also wanted to determine whether sorting would change across time (d 7 vs. 21) or if there was any day $\times$ treatment interaction. There was no significant day $\times$ treatment interaction on sorting of any of the screens. There was a small but statistically significant day effect on sorting of 8.98-mm screen ($P = 0.001$), which was 99.8% on d 7 and 98.6% on d 21.

Milk Production and Milk Composition

Increasing cGMPL linearly decreased milk production ($P = 0.004$) and true protein yield ($P = 0.003$) (Table 4). Cows decreased milk production by 0.91 kg/d and protein yield by 31 g/d for each 1-mm increment in cGMPL. The decreased milk production and true protein yield was probably due to a lower energy intake, related to a lower DMI. When the actual dietary DMI was used in the NRC (2001) program to estimate theoretical milk production differences between diets, the difference between LOS and the average of the 2 finest diets (FMOS and FLOS) was predicted to be 3.4 kg/d. The difference detected in the present experiment was 1.1 kg/d. Therefore, some other factors might have been affecting milk production. One possible explanation is that cows fed LOS sorted in favor of smaller particles, which consisted mainly of grain; therefore, they ingested a diet with a higher energy content than the one offered. Concurrently, increased cGMPL could have resulted in increased retention time and increased total tract digestibility, therefore partially compensating for the lower DMI. Dry matter intake significantly affected true protein yield ($P = 0.002$; data not shown), and the linear effect of GMPL became a trend ($P = 0.10$; data not shown) after the

introduction of DMI into the model as a covariate. The decreased milk true protein yield was probably the result of the lower DMI. There were no significant linear or quadratic effects of cGMPL on fat and true protein percentage or fat yield.

Particle size distribution had a significant effect on milk composition. Feeding a mixture of long and finely chopped oat silage (LFLOS) reduced milk fat percentage ($P = 0.05$) and yield ($P = 0.05$) compared with medium chopped oat silage. It is not clear why cows fed MOS produced more milk fat than cows fed LFLOS. Numerically, cows fed FMOS produced less milk fat than cows fed FLOS; thus the difference caused by PDS does not appear to be related to different silage fermentation. Therefore, contrary to our hypothesis, other factors, such as PSD, affected some of the variables measured.

Chewing Activities

The overall time spent eating ranged from 3.8 to 4.5 h/d, and time spent ruminating ranged from 8.8 to 9.2 h/d (Table 5). The time spent eating and ruminating the 2 finer diets (FMOS and FLOS) was similar to that reported for the coarser diets fed in Krause and Combs (2003), which had a GMPL similar to FMOS and FLOS. Beauchemin et al. (1994) reported that healthy high-producing cows should ruminate >6 h/d. Sudweeks et al. (1981) also suggested that to limit the risk of digestive disorders, cows should chew at least 30 min/kg of DMI. In the present study, cows' chewing activity ranged from 35.3 to 41.5 min/kg of DMI. Time spent chewing per kg of DMI and overall time ruminating suggest that animals in the present study were not prone to digestive disorders.

Total time spent eating ($P = 0.02$) and chewing ($P = 0.003$) increased linearly with increasing cGMPL.

Table 6. Effect of different geometric mean particle length (GMPL), particle size distribution (PSD), and silo on ruminal pH, NH₃, and VFA.

Item	Diet ¹					SEM	Statistical contrast ²			
	FMOS	FLOS	MOS	LFLOS	LOS		Linear	Quadratic	PSD	Silo
pH	6.11	6.25	6.27	6.26	6.27	0.08	0.28	0.40	0.87	0.16
NH ₃ , mg/dL	11.9	11.8	10.0	12.0	9.9	0.8	0.11	0.98	0.12	0.93
VFA, mM	106.7	100.0	96.7	100.8	100.3	4.3	0.55	0.41	0.55	0.34
	(mol/100 mol)						(P)			
Acetate (A)	57.6	56.1	59.1	55.3	59.1	1.5	0.33	0.63	0.12	0.49
Propionate (P)	24.9	28.0	26.7	28.2	24.7	1.8	0.54	0.31	0.55	0.27
Butyrate	12.6	12.0	11.5	11.3	11.5	0.6	0.21	0.29	0.75	0.39
A:P	2.41	2.04	2.35	2.02	2.64	0.27	0.33	0.42	0.45	0.39

¹FMOS = Fine from medium oat silage, FLOS = fine from long oat silage, MOS = medium oat silage, LFLOS = 50% long oat silage and 50% fine from long oat silage, and LOS = long oat silage.

²Statistical contrast: linear and quadratic effects of different GMPL; effect of different PSD but similar GMPL (MOS vs. LFLOS); effect of silo fermentation characteristics but similar GMPL (FMOS vs. FLOS).

Cows increased time spent eating by 19.1 min/d and time spent ruminating by 10.5 min/d for each 1-mm increment in cGMPL. The increased time spent eating and chewing was a result of an increased time spent eating and chewing per kg of DMI. Time spent ruminating per kg of DMI also increased linearly, increasing cGMPL. Cows increased time spent eating by 1.42 min/kg of DMI and time spent ruminating by 1.70 min/kg of DMI for each 1-mm increment in cGMPL. It has been shown in various experiments that increasing GMPL increased time spent eating and ruminating per kilogram of DMI (Soita et al., 2000; Beauchemin et al., 2003; Krause and Combs, 2003). Cows fed MOS tended ($P = 0.09$) to spend less time eating per kilogram of DMI than cows fed LFLOS. We defined the action of eating as a mouth movement that does not include ruminating, drinking, or social exchanges; therefore, it includes activity such as moving feeds around in the manger, provided a jaw move is involved. It is possible that the increased total eating time and time spent eating per kilogram of DMI for LFLOS vs. MOS was due to cows spending more time sorting LFLOS than MOS.

In the present experiment, cumulative percentage on and above the 1.65-mm screen was similar across treatments and was 79.0% for FMOS, 78.6% for FLOS, 81.3% for MOS, 80.2% for LFLOS, and 81.3% for LOS. However, the cumulative percentage on and above the 1.65-mm screen was similar across treatment time spent ruminating per kilogram of DMI increased with increasing cGMPL, indicating that the dietary percentage retained on a sieve with a diagonal opening of 1.65 mm does not provide the best estimate of peNDF. Similarly, Kononoff and Heinrichs (2003) conducted a study in which they tested alfalfa silage with different GMPL but a similar fraction retained above a screen of

1.18 mm. Feeding diets with increasing GMPL linearly increased DMI and total chewing activity per kilogram of DMI (Kononoff and Heinrichs, 2003). Therefore, 2 recent experiments have showed that the percentage of the diet retained on a sieve with an aperture of 1.18 mm does not provide the best estimate of peNDF.

Rumen Measurements

There were no significant differences in rumen pH, total VFA concentration, molar proportion of individual VFA, and NH₃ between FMOS and FLOS or between MOS and LFLOS (Table 6). There was a treatment $\times$ time interaction for rumen pH (Figure 3). The interaction, however, is not clear; the major differences across diets seemed to be at 8 and 12 h after the morning feeding. Eight hours after feeding, the ruminal pH of cows fed MOS did not drop as much as that of cows fed the other diets, and it stayed stable after that. Mean ruminal pH was >6 for all dietary treatments (Table 6), and there was no significant linear or quadratic effect of cGMPL on mean ruminal pH. Furthermore, there was also no significant linear or quadratic effect of cGMPL on total VFA concentration or molar proportion of the various volatile fatty acids. Krause et al. (2002b) reported an increase in mean ruminal pH with increasing forage particle length. Kononoff and Heinrichs (2003) reported that modifying dietary particle length through replacing short alfalfa haylage with long alfalfa haylage at different levels resulted in a quadratic increase in mean ruminal pH. Various experiments reported that mean ruminal pH was not correlated to dietary mean particle length (Yang et al., 2001; Beauchemin et al., 2003).

In Krause et al. (2002b), overall average ruminal pH was 5.92 and was lower than the average pH ob-

Table 7. Effect of different geometric mean particle length (GMPL), particle size distribution (PSD), and silo on in situ DM and NDF disappearance of soybean hulls after 24 h of incubation and ruminal Cr-mordanted straw and liquid outflow rates.

Item	Diet ¹					SEM	Statistical contrast ²			
	FMOS	FLOS	MOS	LFLOS	LOS		Linear	Quadratic	PSD	Silo
In situ disappearance	(%)						(P)			
DM	73.0	75.0	74.5	74.4	74.4	2.7	0.88	0.88	0.98	0.57
NDF	44.7	49.2	49.4	48.6	47.8	5.9	0.87	0.72	0.91	0.57
Rumen	(%/h)									
Straw outflow rate ³	4.1	4.0	4.6	3.9	4.5	0.2	0.10	0.92	0.03	0.48
Liquid outflow rate	10.3	10.1	10.8	9.9	9.7	0.5	0.32	0.45	0.11	0.72

¹FMOS = Fine from medium oat silage, FLOS = fine from long oat silage, MOS = medium oat silage, LFLOS = 50% long oat silage and 50% fine from long oat silage, and LOS = long oat silage.

²Statistical contrast: linear and quadratic effects of different GMPL; effect of different PSD but similar GMPL (MOS vs. LFLOS); effect of silo fermentation characteristics but similar GMPL (FMOS vs. FLOS).

³Straw outflow rate = Cr-mordanted straw outflow rate.

served in the present experiment. In Krause et al. (2002b), the increased chewing activity resulted in increased average ruminal pH, probably because of an increased saliva flow. Sodium bicarbonate, which is the major buffer in saliva, has a pH of 6.25. Therefore, saliva addition through increasing chewing activity at ruminal pH close to 6.25 should not increase ruminal pH to the same extent as at a ruminal pH <6.0, probably explaining the difference between experiments.

Ruminal rate of passage of Cr-mordanted straw and liquid phase were not affected by cGMPL (Table 7). Overall rates were similar to values reported by Krause et al. (2002a). Feeding LFLOS reduced Cr-mordanted straw rate of passage compared with feeding MOS ($P = 0.03$). Feeding either FLOS or LOS alone resulted in a faster Cr-mordanted straw rate of pas-

sage than feeding a mixture of the 2 (LFLOS); therefore, the slower Cr-mordanted straw rate of passage of LFLOS compared with MOS is not simply related to GMPL and appeared to be influenced by PSD. It seems that feeding the 2 together resulted in an interaction. There is no clear explanation for this difference; however, other variables measured support this effect.

Mourino et al. (2001) measured cellulose degradation in an in vitro system at various pH values. It was suggested that the initial pH of the incubation affected the rate at which cellulose was digested (Mourino et al., 2001). A model was proposed under which the adhesion of cellulolytic bacteria to fiber particles would decrease if initial pH was between 5.3 and 6.0 (Mourino et al., 2001). In the present experiment, bags were incubated every 4 h to have different initial pH and

Table 8. Linear effect of either dietary geometric mean particle length (dGMPL) or geometric mean particle length of diet consumed (cGMPL) on dependent variables where significant linear effect of GMPL was reported.

Dependent variable		Statistic ¹		
		P	RE	AIC
DMI, kg/d	dGMPL	0.0009	1.51	221
	cGMPL	0.003	1.60	223
Milk, kg/d	dGMPL	0.003	1.98	256
	cGMPL	0.001	1.91	254
Milk protein yield, g/d	dGMPL	0.0006	0.0019	-109
	cGMPL	0.0003	0.0019	-111
Eating, min/d	dGMPL	0.04	1518	569
	cGMPL	0.13	1602	571
Eating, min/kg of DMI	dGMPL	0.002	4.31	260
	cGMPL	0.02	4.81	263
Ruminating, min/d	dGMPL	0.11	879	558
	cGMPL	0.05	837	554
Ruminating, min/kg of DMI	dGMPL	<0.0001	3.63	270
	cGMPL	<0.0001	3.56	270

¹The model included period, square, cow within square, and the linear effect of either dGMPL or cGMPL. P = linear effect of either dGMPL or cGMPL, RE = residual estimate, and AIC = Akaike's information criterion.

verify the effect of initial pH on NDF degradability in an in vivo system. Time of incubation did not affect DM and NDF disappearance, and treatments did not differ across time. However, the within-treatment average initial pH was never <5.9. Therefore, the lack of time effect could be due to the initial rumen pH being borderline high in the range suggested by Mourinio et al. (2001). In situ DM and NDF disappearance of soybean hulls after 24 h of incubation were similar across treatments (Table 7). Batajoo and Shaver (1998) reported similar DM disappearance of soybean hulls after 24 h of incubation in the rumen; however, NDF disappearance was not measured.

dGMPL vs. cGMPL

Response variables that were measured on a cow can be categorized into 2 groups: variables affected by what the cow has been offered and variables affected by what the cow actually ate. The first group should probably include DMI and time spent eating as min/d and min/kg of DMI, especially if eating time, as previously suggested, also included time spent sorting feed. Conversely, other variables such as milk production, milk protein yield, and time spent ruminating both as min/d and min/kg of DMI should be affected only by what the cow actually ate. Therefore, dGMPL should better explain DMI and time spent eating, whereas cGMPL should better explain the remaining variables. This was generally in agreement with the *P* values and fit statistics reported in Table 8. Milk yield and time spent ruminating as min/d were better explained by cGMPL than by dGMPL. Utilizing cGMPL vs. dGMPL in the model decreased the possibility of a nonsignificant effect of GMPL. The residual error and the Akaike's information criterion values decreased, indicating a better fit to the data for cGMPL than for dGMPL. Time spent eating both as min/d and min/kg of DMI were better explained by dGMPL than by cGMPL. For time spent ruminating as min/kg of DMI, the effect of either dGMPL or cGMPL was highly significant ($P < 0.0001$), the Akaike's information criterion values were the same, and residual error was slightly smaller for cGMPL than for dGMPL. Overall, the inclusion of sorting in GMPL better explained those dependent variables likely to be affected by what the cow actually consumed.

CONCLUSIONS

Dietary geometrical mean particle length appears to be a good predictor of animal response independent of the particle size distribution. Because particles

longer than 26.9 mm may be selected against by some cows, to obtain a uniform response across the entire herd, it is better to achieve adequate mean particle length with the least amount of particles longer than 26.9 mm and the greatest amount of particles between 26.9 and 9 mm.

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