Effects of Forage Particle Size and Grain Fermentability in Midlactation Cows. I. Milk Production and Diet Digestibility

K. M. Krause,* D. K. Combs,* and K. A. Beauchemin†

*Department of Dairy Science,
University of Wisconsin, Madison 53706

†Research Centre, Agriculture and Agri-Food Canada,
Lethbridge, AB, Canada T1J 4B1

ABSTRACT

Our study investigated the effects of, and interactions between, level of dietary ruminally fermentable carbohydrate (RFC) and forage particle size on milk production, nutrient digestibility, and microbial protein yield for dairy cows fed one level of dietary NDF. Eight cows (61 days in milk) were assigned to four treatments in a double 4×4 Latin square. Treatments were arranged in a 2×2 factorial design; finely chopped alfalfa silage (FS) and coarse alfalfa silage (CS) were combined with concentrates based on either dry cracked shelled corn (DC; low RFC) or ground high-moisture corn (HMC; high RFC). Diets were fed *ad libitum* as a total mixed rations with a concentrate to forage ratio of 61:39. Diets based on DC had a predicted NE_L content of 1.73 Mcal/kg dry matter (DM), while HMC diets contained 1.80 Mcal/kg DM. Diets averaged 18.7% CP, 24.0% NDF, 18.3% ADF, and 27.4% starch on a DM basis. Mean particle size of the four diets was 6.3, 2.8, 6.0, and 3.0 mm for DCCS, DCFS, HMCCS, and HMCFS, respectively. Increasing level of RFC decreased dry matter intake (DMI) from 25.0 to 23.8 kg/d and organic matter intake from 22.3 to 21.1 kg/d, but intake was not affected by particle size. Milk production averaged 44.0 and 26.8 kg/d solids corrected milk (SCM) and was not affected by diet, but increasing level of RFC tended to increase milk yield. Efficiency of milk production, expressed as SCM/DMI, increased from 1.06 to 1.14 when level of RFC was increased. Milk composition or yield of milk components was not affected by diet, and averaged 3.53% fat, 3.11% protein, 1.55 kg/d fat, and 1.36 kg/d protein. Total tract digestibility of DM and OM increased from 71.4 to 73.0% and 72.4 to 76.1% for DM and OM, respectively, when level of RFC was increased. Total tract digestibility of fiber was unaffected by diet, but total tract

starch digestibility increased from 93.1 to 97.4% when HMC replaced DC. Total urinary excretion of the purine derivatives uric acid and allantoin increased from 415 to 472 mmol/d when level of RFC was increased, and calculated microbial N supply increased from 315 to 365 g/d. When expressed as per kilogram of digestible OMI, increasing level of RFC tended to increase microbial N supply (20.4 vs. 22.2 g/kg). Cow productivity was not affected by forage particle size and ruminally fermentable carbohydrates in this study.

(**Key words:** particle size, ruminally fermentable carbohydrate, production, digestibility)

Abbreviation key: CS = coarse silage, DC = dry corn, DOMI = digestible organic matter intake, eNDF = effective NDF, ERD = effective rumen degradability, FS = fine silage, HMC = high moisture corn, RFC = ruminally fermentable carbohydrate.

INTRODUCTION

Energy and fiber requirements of dairy cows in early lactation are not easily met because their energy expenditure exceeds the energy consumed. Diets high in starch and low in fiber are fed to increase intake of energy, but these diets increase the risk of ruminal acidosis.

Milk fat percentage response (Armentano and Pereira, 1997), time spent chewing (Sudweeks et al., 1981), and ruminal pH (Mertens, 1997) have been used to determine the effectiveness of fiber in diets for dairy cows. The effectiveness of NDF is related to the total ability of a feed to replace forage in a ration so that the percentage of fat in milk produced by cows eating the ration is effectively maintained (Mertens, 1997). Diets low in effective fiber and high in fermentable carbohydrates can affect ruminal fermentation negatively. *In vitro* studies have shown that fiber digestion is greatly depressed when pH declines below 6.0, and that the optimal ruminal pH for fiber digestion is around 6.5 (Shriver et al., 1986). However, ruminal pH of growing cattle and high producing dairy cows is often below 6.0 despite diets balanced to include a

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Corresponding author: D. K. Combs; e-mail: dkcombs@facstaff.wisc.edu.

minimum amount of forage to ensure rumen function. A decrease in fiber digestion because of low ruminal pH can decrease ruminal digestion of the diet (Shriver et al., 1986) and, therefore, negatively affect production.

The Cornell Net Carbohydrate and Protein System indicates that diets containing less than 20% NDF from forage reduce microbial yield (Russell et al., 1992). Strobel and Russell (1986) reported that mixed ruminal bacteria incubated in vitro with a mixed carbohydrate substrate produced 13.6 mg DM/mmol ATP produced at pH 5.7 versus 21.2 mg DM/mmol ATP produced at pH 6.7. Depression in carbohydrate utilization at low pH is a primary factor contributing to the lower protein yield, but this does not completely explain the decrease in protein yield. Because certain amino acids are often limiting postruminally (NRC, 2001), depressions in microbial protein synthesis could have a negative effect on animal productivity. However, information is lacking concerning the in vivo effects of diets low in effective fiber and high in fermentable carbohydrates on the protein yield of rumen microbes.

The objectives of this study were to investigate the effects of, and interactions between, level of ruminally fermentable carbohydrate in the diet and forage particle size on milk production, digestibility, and microbial yield at constant level of dietary NDF.

MATERIALS AND METHODS

Cows and Diets

Eight multiparous Holstein cows were assigned randomly to one of two squares in a double 4×4 Latin square. Cows were fitted with ruminal cannulas and averaged 61 ± 8 DIM at the start of the experiment. Average BW was 580 ± 49 kg at the beginning of the experiment and 617 ± 53 kg at the end of the experiment. Experimental periods were 28 d in duration (16 d of treatment adaptation and 12 d of data collection). Treatments were arranged in a 2×2 factorial design; two levels of forage particle size (fine and coarse) were combined with concentrates based on either dry cracked shelled corn (**DC**; 89.9% DM) or ground high-moisture shelled corn (**HMC**; 74.2% DM). The high-moisture shelled corn was treated with propionic acid (6.7 kg/tonne) during ensiling. Dry cracked shelled corn and ground high-moisture shelled corn were used in this trial because of their differences in ruminal starch degradability. One report from the literature indicated that 65 and 86% of the starch in dry cracked shelled corn and in high-moisture corn is degraded in the rumen, respectively (Nocek and Tamminga, 1991). Dry cracked corn was also used because its mean parti-

cle size was very similar to the particle size of the high-moisture corn, whereas the dry ground corn available for this trial was ground finer than the high-moisture corn. First-cut, wilted alfalfa silage that was harvested at the early bloom stage of maturity was the sole source of forage. The forage was chopped with a Gehl Implement, model number 865 forage chopper (Gehl Implement, West Bend, WI), with a head model number 1210 adjusted to cut forage at 1.9-cm theoretical length of cut. Forage was ensiled in a 3.7×12.2 m concrete stave silo. This silage provided the coarse silage (**CS**) for the diets. Finely chopped silage (**FS**) was obtained by recutting the ensiled alfalfa silage through a 1.9-cm screen in a forage recutter (Gehl) daily for the duration of the trial. Geometric particle size of the forages and the corn grain is given in Table 1. All diets were formulated to meet or exceed the requirements of a 600-kg multiparous cow producing 45 kg of milk/d using CPM-Dairy (1997). Diet formulations are given in Table 2.

Diets were fed as a TMR with a ratio of concentrate to forage of 61:39 (DM basis). Cows were fed ad libitum (10% refusals), and feed was offered twice daily at 0700 and 1900 h in equal portions. Intake and milk production were recorded daily throughout the experiment. Feed and ort samples were taken twice weekly, and intakes of nutrients were corrected for nutrient contents of orts. Dry matter (60°C) of feed components was determined weekly, and diets were adjusted to account for changes in DM content.

Cows were cared for according to guidelines of The Research Animal and Resource Committee of the Univ. of Wisconsin-Madison, and all experimental procedures performed on the animals were approved. Cows were housed in stalls bedded with rubber mattresses and wood shavings and were milked twice daily at 0300 and 1500 h in a milking parlor. Cows were turned outside for 1 to 2 h daily after being milked, except on days when total urine output was recorded. Milk was sampled on consecutive p.m. and a.m. milkings on 2 d during each period, and milk components were determined by AgSource, Menomonie, Wisconsin, using a near-infrared reflectance spectroscopy analyzer (Milkoscan 605; Foss Electric, Hillerød, Denmark).

Feed Analysis

Composite samples of all feeds, diets, and orts were obtained during each experimental period. Dried samples were ground to pass a 1-mm screen (Wiley Mill, Arthur H. Thomas, Philadelphia, PA). Analytical DM content of feeds was determined by oven-drying at 135°C for 2 h; OM was determined by ashing at 500°C for 16 h, and CP was determined by the micro-Kjeldahl

Table 1. Mean geometric particle size of corn grain, forage, and TMR.

	Mean (mm)	SD (mm)
Dry cracked shelled corn ¹	1.55	0.06
High-moisture shelled corn	1.60	0.13
Coarse alfalfa silage ²	13.6	1.6
Fine alfalfa silage	3.7	0.4
HMCFS ³	3.0	0.2
HMCCS	6.0	0.6
DCFS	2.8	0.3
DCCS	6.3	0.6

¹Mean geometric particle size of corn grain was determined by dry-sieving according to ASAE (1995) standards.

²Mean geometric particle sizes of forages and TMR were determined by dry-sieving using the UW forage particle size separator in accordance with ASAE standard S424 (1988). Diagonal diameters of openings in screens were: 26.90, 18.00, 8.98, 5.61, and 1.65 mm. Distribution of particles, in percent of total mass, on the five screens and the pan, respectively, were: Coarse alfalfa silage: 20.3, 21.4, 34.5, 8.9, 10.7, 4.2; fine alfalfa silage: 0.3, 0.2, 18.1, 19.1, 44.8, 17.5; HMCFS: 0.0, 0.1, 15.1, 18.5, 35.3, 31.1; HMCCS: 6.7, 15.6, 24.2, 14.8, 16.6, 21.9; DCFS: 0.0, 0.0, 11.0, 19.4, 39.1, 30.5; DCCS: 8.3, 16.2, 20.9, 15.2, 20.0, 19.4.

³Treatments: HMCFS = High-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = dry corn and fine silage, DCCS = dry corn and coarse silage.

method (AOAC, 1990). The NDF fraction was determined using α -amylase (Sigma no. A3306; Sigma Chemical Co., St. Louis, MO) and sodium sulfite (Van

Soest et al., 1991) and was not corrected for ash content; ADF was determined using the procedure described by Goering and Van Soest (1970). Starch was

Table 2. Composition and nutrient content of dietary treatments.

	Treatments ¹			
	HMCFS	HMCCS	DCFS	DCCS
Feed stuff, % of DM				
Alfalfa silage ² , fine	39.3	...	39.3	...
Alfalfa silage ² , coarse	...	39.3	...	39.3
High-moisture shelled corn	36.6	36.6	...	...
Dry cracked shelled corn	...	...	36.6	36.6
Wheat middlings	9.4	9.4	9.4	9.4
Corn gluten meal	3.1	3.1	3.1	3.1
Soybean, whole roasted	7.9	7.9	7.9	7.9
Soybean meal, 44%	2.0	2.0	2.0	2.0
Blood meal	0.6	0.6	0.6	0.6
Smartamine™ ML ³	0.2	0.2	0.2	0.2
Dicalcium phosphate	0.2	0.2	0.2	0.2
Calcium carbonate	0.2	0.2	0.2	0.2
ADE vitamin mix ⁴	0.1	0.1	0.1	0.1
Salt and trace mineral mix ⁵	0.4	0.4	0.4	0.4
NE _L ⁶ , Mcal/kg DM	1.80	1.80	1.73	1.73
DM, %	58.7	58.6	63.3	60.0
OM, % of DM	93.7	93.6	93.8	93.7
CP, % of DM	18.6	18.5	18.8	18.8
NDF, % of DM	24.8	23.2	23.4	24.6
eNDF ⁷ , % of DM	14.4	13.6	14.4	13.6
ADF, % of DM	19.0	17.7	17.8	18.8
Starch, % of DM	28.2	29.0	26.9	25.2

¹Treatments: HMCFS = High-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = dry corn and fine silage, DCCS = dry corn and coarse silage.

²Alfalfa silage contained 41.9% DM, 19.3% CP, 36.7% NDF, and 29.9% ADF on a DM basis.

³Rhône-Poulenc Animal Nutrition, 500 Northridge Road, Atlanta, GA 30350, USA.

⁴3308 IU of vitamin A/g, 1103 IU of vitamin D/g, and 11.03 IU of vitamin E/g.

⁵0.55% Mn, 0.55% Zn, 0.35% Fe, 0.14% Cu, 0.008% I, 0.006% Se, and 0.002% Co.

⁶Based on tabular values.

⁷Estimated using the eNDF values of 0.87 for coarse silage and 0.75 for finely chopped silage as suggested by Mertens (1997).

determined by a colorimetric assay including a pure cornstarch sample as described by Bal et al. (2000).

Particle size of forages and TMR was determined by dry-sieving using an oscillating screen particle size separator according to ASAE standard S424 (Am. Natl. Standards Inst., 1988). Particle size of the corn grain was determined by dry-sieving according to ASAE (1995) standards.

Digestibility

Lanthanum in solution (0.2 g/ml) was used as a marker to measure total tract digestibility (Hartnell and Satter, 1979) and was ruminally dosed at 12-h intervals for the last 14 d of each period to provide 0.8 g of La per cow per day. Fecal samples were collected at different times of the day during a 5-d interval concurrent with fecal sampling for rate of passage measurements. Sampling times differed such that the entire 24-h day was represented to account for possible diurnal variation. Fecal samples were dried, ground to pass a 1-mm screen, pooled by period for each cow and dry-ashed at 500°C for 16 h. Concentrations of La were determined by direct current plasma emission spectroscopy (Spectra Metrics, Inc., subsidiary of Beckman Instruments, Inc., Andover, MA; Combs and Satter, 1992). Total tract nutrient digestibilities were calculated from fecal La concentration and nutrient concentrations in diets fed *orts* and feces.

In Sacco Measurements

Ruminal degradation of TMR was measured using large (25 × 35-cm), *in situ* bags made of Dacron polyester cloth with a pore size of $52 \pm 5 \mu$. Approximately 80 g (as fed) of whole TMR samples were weighed into bags, soaked in warm water for 10 min, and placed in large mesh retaining sacs before being incubated ruminally for 0, 3, 4, 5, 6, 12, 24, 48, and 96 h. Only one bag per time point was incubated for 3, 4, 5, and 6 h, whereas other time points were done in duplicate. After removal from the rumen, bags were washed under cold, running tap water, and then machine-washed twice in cold water using a rinse cycle with 2 min of agitation. The 0 h time point bags were not placed in the rumen, but were subject to the same washing procedure. Bags were dried at 60°C for 72 h.

The kinetics of DM disappearance in sacco were estimated using nonlinear least squares (PROC NLIN of SAS; SAS, 1998). For each cow and period, the following model (McDonald, 1981) was fitted to the percentage of DM disappearance:

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

where a = soluble fraction (%); b = slowly digestible fraction (%); k_d = fractional rate of disappearance ($\%h^{-1}$); L = lag time (h); and t = incubation time (h). The indigestible fraction, referred to as 'c' in the results, was calculated by difference.

Rate of Passage

Lithium-Co-EDTA and Cr-mordanted fiber were prepared as described by Udén et al. (1980) and used as markers for liquid and solid passage rates, respectively. The Li-Co-EDTA was dried and ground using a mortar and pestle; Cr-mordanted fiber was prepared by mordanting wheat straw NDF ground through a 6-mm screen using a Wiley mill. Markers were placed in the rumen at the time of the morning feeding, and no attempt was made to manually mix markers with rumen contents. Fecal grab samples were taken at 0, 6, 10, 14, 18, 22, 26, 30, 36, 42, 48, 54, 60, 72, 84, 96, and 120 h after dosing to determine the rate of passage. Samples were dry-ashed, 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; Combs and Satter, 1992).

Fecal Cr and Co excretion curves were fitted to the double-compartment model represented by two exponential constants and a time delay (Grover and Williams, 1973):

$$Y = Ae^{-k_1(t-TT)} - Ae^{-k_2(t-TT)}, \quad k_1 < k_2 \text{ for } t \geq TT \\ Y = 0 \text{ for } t < TT,$$

where Y = marker concentration (ppm); A = scale parameter; k_1 = ruminal rate of passage ($\%/h$); k_2 = lower digestive tract rate of passage ($\%/h$); t = sampling time post dosing (h); and TT = transit time. Total mean retention time in the digestive tract was calculated as the sum of retention in the rumen ($1/k_1$) and in the lower digestive tract ($1/k_2$) plus the transit time (TT). Data were analyzed by nonlinear regression using the NLIN (iterative Marquardt method) procedure of SAS (SAS, 1998).

Microbial Protein Synthesis

Microbial protein synthesis was not measured directly. Instead, the urinary excretion of the purine derivatives allantoin and uric acid were used as an estimate of microbial N flow to the duodenum. On three consecutive days in each experimental period, total urine was collected using indwelling catheters (24"-, 75-cc balloon lubricious catheter, C. R. Bard, Inc., Covington, CA). Containers with 500 ml of 1.5 N H_2SO_4

were attached to each cow, and output of urine was measured twice daily. After recording the volume of urine excreted, acidified urine was mixed, and 20-ml samples were taken, diluted to 100 ml with tap water and frozen (-20°C) for later analysis. Concentration of allantoin in urine was determined colorimetrically using the method described by Chen and Gomes (1992) however, 1 M HCl was used instead of 0.5 M HCl in the assay in order to keep pH <3. Samples were diluted 10 times with tap water in the laboratory to a final dilution of 50 before analysis. Uric acid in urine was determined colorimetrically using a diagnostic uric acid reagent (procedure no. 685, Sigma Diagnostics). For the uric acid assay, 1 ml of reagent was used with 50 μl of urine diluted 25 times (samples were diluted five times with tap water in the lab before analysis). Purine absorption and intestinal flow of microbial N was calculated using the assumptions and equations given by Chen and Gomes (1992). The quantitative relationship between absorption of microbial purines (X mmol/d), and excretion of purine derivatives in urine can be described by the following equation:

$$Y = 0.85X + (0.0385 W^{0.75}),$$

where $W^{0.75}$ represents the metabolic BW (kg) of the animal. The slope of 0.85 represents the recovery of absorbed purines as purine derivatives in urine. The component within parenthesis represents the net endogenous contribution of purine derivatives to total excretion after correction for the utilization of microbial purines by the animal. The following factors were used to calculate intestinal flow of microbial N (g N/d) from the microbial purines absorbed (X mmol/d): Digestibility of microbial purines was assumed to be 0.83; the N content of purines was 70 mg N/mmol; and the ratio of purine-N to total N in mixed rumen microbes was taken as 11.6:100. Thus, microbial N was calculated as:

$$\text{Microbial N supply (g/d)} = (X \times 70) / (0.83 \times 0.116 \times 1000) = 0.727 \times X$$

This assumes that the purine to protein ratio in mixed rumen microbes was unchanged by dietary treatment.

Statistical Analysis

Data on all variables were analyzed using the mixed model procedure in SAS (SAS, 1998); period, level of RFC, particle size of forage, and the interaction of RFC and forage were fixed effects in the model, and period was used as a repeated measurement with first-order auto regressive covariance structure. The random statement included square and cow within square. The

model used for intake and production variables, digestibilities and purine derivative excretion data is shown below.

$$Y_{ijklm} = \mu + S_i + C_{j(i)} + P_k + M_l + F_m + (M \times F)_{lm} + e_{ijklm},$$

where μ = overall mean; S_i = random effect of square ($i = 1$ to 2); $C_{j(i)}$ = random effect of cow within square ($j = 1$ to 4); P_k = fixed effect of period analyzed as repeated measurements ($k = 1$ to 4); M_l = fixed effect of level of RFC ($l = 1$ to 2); F_m = fixed effect of forage particle size ($m = 1$ to 2); $(M \times F)_{lm}$ = fixed effect of interaction of M_l and F_m ; and e_{ijklm} = random residual error, assumed to be normally distributed. Significance was declared at $P \leq 0.05$. A trend was considered to exist if $0.05 < P \leq 0.10$. All reported values are least square means unless otherwise stated.

RESULTS AND DISCUSSION

Feed Particle Size and Intakes

Analysis of particle size of forage indicated that the alfalfa silage was coarsely chopped (Table 1). The geometric mean particle size of 13.6 mm was considered to be above the threshold of 6.4 mm that is reported to reduce rumination time and cause milk fat depression when dairy cows are fed chopped alfalfa hay as forage (Woodford et al., 1986). The mean geometric particle size of the finely chopped silage was below this threshold. All diets used in this study were relatively low in NDF (Table 2). Based on the low NDF content of the diets and the small particle size of the finely chopped forage, the diets based on finely chopped silage were predicted to be inadequate in level of effective NDF.

Based on the diagonal diameter of the screens in the UW forage particle size separator (ASAE standard S424, American National Standards Institute, 1988), the two top screens of the UW forage particle size separator represent the top screen of the Penn State particle size separator, whereas screen number three represents the middle screen of the Penn State particle size separator and the last two screens the pan. Using this approximation, the forages and TMR had the following distribution on the top screen, middle screen, and pan of the Penn State particle size separator (% as fed): CS: 41, 35, 24; FS: 0, 18, 82; HMCFS: 0, 15, 85; HMCCS: 22, 24, 54; DCFS: 0, 11, 89; DCCS: 24, 22, 55.

Intakes of DM, OM, and nutrients are shown in Table 3. Intakes of DM and OM were higher for DC than for HMC diets. Other studies have found no difference in DMI when comparing dry corn versus high-moisture corn fed to dairy cows (Knowlton et al., 1998; Ying et

Table 3. Effects of level of ruminally fermentable carbohydrates and forage particle size on intake.

Intake, kg/d	Treatments ¹				SED ²	Statistical significance (<i>P</i> -value)		
	HMCFS	HMCCS	DCFS	DCCS		RFC ³	Forage	RFC × Forage
DM	23.4	24.1	24.7	25.3	0.7	0.01	0.12	0.89
OM	20.8	21.3	22.0	22.6	0.6	0.0095	0.19	0.98
NDF	5.59	5.18	5.38	5.82	0.28	0.30	0.92	0.05
eNDF ⁴	3.17	3.11	3.05	3.49	0.16	0.27	0.11	0.05
ADF	4.22	3.91	4.08	4.41	0.20	0.24	0.94	0.04
Starch	6.39	6.91	6.80	6.18	0.34	0.51	0.85	0.03

¹Treatments: HMCFS = High-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = Dry corn and fine silage, DCCS = dry corn and coarse silage.

²SED = Standard error of difference.

³RFC = Ruminally fermentable carbohydrate.

⁴Estimated by multiplying NDF intake with percent eNDF of total NDF.

al., 1998). However, the effect of corn moisture on DMI seems to depend on level of corn in the diet (Oba and Allen, 2000a). Intake of DM decreased when high-moisture corn replaced dry corn in diets containing 31% starch but not in diets containing 21% starch (Oba and Allen, 2000a). Diets fed in the current study were intermediate in starch content; 28.6% for HMC diets and 26.1% for DC diets.

Forage particle size did not affect DMI in the current study. This is consistent with other studies feeding diets above 40% concentrate (Shaver et al., 1986; Woodford et al., 1986). However, in a study by Woodford and Murphy (1988), reducing forage particle size by replacing alfalfa silage with alfalfa pellets (28% of diet DM) in diets fed to early lactation cows (<90 DIM) decreased DMI. When feeding poor-quality forages (Moore et al., 1964) or high-forage diets (Osuji et al., 1975), reducing forage particle size significantly increased DMI.

An interaction between RFC and forage particle size was observed for NDF, ADF, and starch intake. When cows were fed HMC, increasing forage particle size decreased NDF and ADF intake, whereas when cows were fed DC, increasing forage particle size increased NDF and ADF intake. Starch intake increased with increasing forage particle size when cows were fed HMC, but decreased with increasing forage particle size when cows were fed DC.

Milk Production

Cows fed HMC tended to produce more milk ($P = 0.08$) compared with cows fed DC (Table 4); however, this increase was observed only for the FS diets. In the literature, milk production responses to HMC are mixed. No significant difference in milk production was observed between cows fed HMC and DC in two studies (Chandler et al., 1975; Knowlton et al., 1998), whereas Clark et al. (1973) observed an increase in milk produc-

tion when cows were fed HMC. A slight decrease in milk production was found by De Brabander et al. (1992) when HMC replaced a control concentrate.

Forage particle size did not affect milk yield, which is not surprising considering the lack of response in DMI when forage particle size was changed. Milk yield tended to increase with increasing forage particle size when cows were fed HMC and tended to decrease when cows were fed DC ($P = 0.06$). The tendency for an interaction of forage particle size and level of RFC might be explained by the changes in fiber and starch intake for HMC and DC diets when forage particle size was increased. A higher milk production for HMC diets with increasing forage particle size could be supported by the shift towards a lower fiber and a higher starch intake, whereas the opposite was true for the DC diets when forage particle size was increased (see Table 3 for nutrient intakes).

Solids-corrected milk yield was unaffected by diet, but tended to increase with increasing corn fermentability ($P = 0.08$). Because of lower DMI of diets containing HMC, efficiency of milk production, expressed as SCM production per unit of DMI, was higher for diets containing HMC than for diets containing DC. Greater ruminal fermentation is associated with higher energetic efficiency, which could explain the higher efficiency of milk production for the HMC diets compared to the DC diets.

Level of ruminally fermentable carbohydrate (RFC) did not affect milk fat content or yield. Oba and Allen (2000a) reported a depression in fat percentage when HMC replaced DC in high-starch diets (31%), but no difference when diets contained 21% starch. Knowlton et al. (1998) found no difference in milk composition between DC and HMC when fed at 42.4% of diet DM. Despite the small particle size of the finely chopped silage, no effect of forage particle size was observed on milk fat percentage or fat yield. It was surprising that

Table 4. Effects of level of ruminally fermentable carbohydrates and forage particle size on milk yield and milk composition.

Dependent production variable	Treatments ¹				SED ²	Statistical significance (<i>P</i> -value)		
	HMCFS	HMCCS	DCFS	DCCS		RFC ³	Forage	RFC × Forage
Milk, kg/d	45.6	43.6	42.9	43.7	1.0	0.08	0.38	0.06
SCM, ⁴ kg/d	41.0	41.1	39.6	40.0	1.1	0.08	0.61	0.98
SCM/DMI	1.76	1.68	1.59	1.59	0.05	0.003	0.27	0.31
Fat, %	3.42	3.60	3.48	3.62	0.16	0.72	0.19	0.86
Fat yield, kg/d	1.55	1.59	1.49	1.57	0.07	0.44	0.26	0.65
Protein, %	3.05	3.12	3.15	3.10	0.05	0.23	0.60	0.09
Protein yield, kg/d	1.38	1.37	1.35	1.33	0.04	0.15	0.51	0.95
Lactose, %	2.10	2.02	2.02	2.00	0.05	0.19	0.16	0.45
Lactose yield, kg/d	0.96	0.88	0.89	0.89	0.04	0.16	0.21	0.17
SNF, %	8.4	8.6	8.7	8.5	0.08	0.20	0.63	0.03
SNF yield, kg/d	3.84	3.76	3.71	3.70	0.09	0.13	0.47	0.61

¹Treatments: HMCFS = High-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = dry corn and fine silage, DCCS = dry corn and coarse silage.

²SED = Standard error of difference.

³RFC = Ruminally fermentable carbohydrate.

⁴SCM = Solids-corrected milk, $SCM = (12.3 \times \text{fat yield, kg/d}) + (6.56 \times \text{solid nonfat yield, kg/d}) - (0.075 \times \text{milk yield, kg/d})$, (Tyrrell and Reid, 1965).

no reduction in milk fat percentage was observed when forage particle size was reduced to 3.7 mm, considering the consistent response to reducing forage particle size found in other studies (Woodford et al., 1986; Woodford and Murphy, 1988) and the significant reduction in time spent chewing when forage particle size was reduced (Krause et al., 2002). Milk fat percentage is the animal response that often is associated with effective NDF (eNDF) content of a ration (Mertens, 1997). Based on the milk fat percentages observed in this study, and the lack of diet effect on milk fat percentage, it can be concluded that all four diets provided adequate amounts of eNDF to sustain milk fat percentage. However, diets containing FS did have numerically lower milk fat percentages than CS diets. The number of animals used in this trial might not have been adequate for detecting differences in milk components caused by dietary treatments.

Milk protein percentage and protein yield were similar across diets. For milk protein percentage, level of RFC and forage particle size tended ($P = 0.09$) to interact; protein percentage increased when forage particle size was increased in HMC diets, whereas it decreased in DC diets. This interaction might have been linked to the interaction between level of RFC and forage particle size on starch and fiber intakes. A higher starch intake for HMC diets when forage particle size increased could support an increase in microbial protein synthesis, which might result in a higher milk protein percentage. Lactose percentage and yield were not affected by diet. As for percent protein, percentage of SNF increased with increasing forage particle size for diets containing HMC, but decreased with increasing forage particle size

for diets containing DC. No effect of diet was found on yield of SNF.

Rate of Passage of Liquids and Solids

Increasing forage particle size increased liquid outflow rate from the rumen (Table 5), probably because of a higher saliva production for cows fed CS. Chewing activity, which is reported in a companion paper (Krause et al., 2002), was found to be higher for cows fed CS compared with FS; therefore, a higher saliva production would be expected for cows fed CS. Ruminal outflow rate of solids was not affected by level of RFC or forage particle size, but level of RFC tended ($P = 0.06$) to decrease ruminal retention. Transit time decreased when forage particle size was increased, and total mean retention time in the GI tract was decreased by increasing forage particle size and also decreased by increasing level of RFC. That mean retention time for solids was decreased with increasing forage particle size can seem surprising, but could be related to the fact that the marker used was ground wheat straw. The small particle size of the ground wheat straw might have allowed it to follow the liquid phase, which had an increased outflow rate when forage particle size was increased.

Digestibilities

Apparent total tract digestibility of DM and OM was higher for HMC than for DC diets, and so was total tract starch digestibility (Table 6). This finding is consistent with several studies (Knowlton et al., 1998; Ying et al., 1998), whereas Oba and Allen (2000b) found that only

Table 5. Effects of level of ruminally fermentable carbohydrates and forage particle size on rate of passage of liquids and solids.

Dependent variable	Treatments ¹					Statistical significance (<i>P</i> -value)		
	HMCFS	HMCCS	DCFS	DCCS	SED ²	RFC ³	Forage	RFC × Forage
Liquid outflow rate, %/h	12.2	13.3	11.4	14.2	1.2	0.96	0.03	0.35
Solid outflow rate								
k_1 , %/h ⁴	4.4	5.0	4.1	4.3	0.7	0.31	0.44	0.71
k_2 , %/h ⁵	16.3	16.3	13.8	21.0	4.9	0.76	0.32	0.32
Transit time, h	12.8	11.6	13.2	9.3	1.2	0.32	0.01	0.13
Rumen retention time, h	23.0	20.8	29.4	26.4	4.1	0.06	0.39	0.89
Mean retention time, h	43.8	39.3	50.6	43.3	3.2	0.03	0.02	0.53

¹Treatments: HMCFS = High-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = dry corn and fine silage, DCCS = dry corn and coarse silage.

²SED = Standard error of difference.

³RFC = Ruminally fermentable carbohydrate.

⁴ k_1 = Ruminal rate of passage.

⁵ k_2 = Lower digestive tract rate of passage.

ruminal starch digestibility increased, while total tract digestibility remained unchanged when HMC replaced DC. Total tract digestibilities of NDF and ADF were not affected by diet and were relatively high considering the type of diets fed. Knowlton et al. (1998) found that HMC tended to decrease total tract fiber digestibility compared with DC.

The ADF digestibility for HMC diets tended to decrease ($P = 0.08$) with increasing particle size when cows were fed HMC. This could be related to retention time, but the opposite occurred for the DC diets. Depressed fiber digestibility has been reported when forage particle size is reduced (Shaver et al., 1986; Woodford and Murphy, 1988). Ruminal pH was also measured in this study, and results are reported by Krause et al. (2002). The mean ruminal pH of 5.72 and 5.90 for HMCFS and DCFS, respectively, are both below the threshold where fiber digestion is inhibited in vitro (Hoover et al., 1984); therefore, it is surprising that fiber digestibility was unaffected by diet in this study.

In a review of the literature, Erdman (1988) found that 0.1-unit decrease in mean ruminal pH in vivo resulted in a 3.6%-unit decrease in ruminal ADF digestibility. In the current study, diets resulting in the lowest ruminal pH had the numerically highest fiber digestibility. Studies by Beauchemin et al. (2000) also found no relationship between ruminal pH and ruminal and total tract NDF digestibility. Starch digestibility tended ($P = 0.06$) to decrease when forage particle size was increased.

Kinetics of ruminal DM digestibility of the diets are shown in Table 7. The soluble DM fraction, *a*, was higher for HMC diets than for DC diets and higher for FS than for CS diets. The slowly digestible DM fraction, *b*, was higher for DC than for HMC diets and increased with increasing forage particle size. The indigestible DM fraction, *c*, was lower for HMC than for DC diets. Lag time was similar across diets. Ruminal rate of digestion, k_a , was unaffected by level of RFC, but increased with increasing forage particle size. Effective

Table 6. Effects of level of ruminally fermentable carbohydrates and forage particle size on total tract digestibilities.

Digestibilities, %	Treatments ¹					Statistical significance (<i>P</i> -value)		
	HMCFS	HMCCS	DCFS	DCCS	SED ²	RFC ³	Forage	RFC × Forage
DM	75.5	74.5	72.8	69.9	1.7	0.01	0.13	0.44
OM	76.6	75.5	73.9	70.8	1.8	0.009	0.12	0.45
NDF	54.3	47.6	46.2	47.7	3.6	0.13	0.33	0.12
ADF	58.9	52.9	51.8	54.2	3.1	0.21	0.43	0.08
Starch	97.7	97.1	94.5	91.6	1.2	0.001	0.06	0.19

¹Treatments: HMCFS = High-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = Dry corn and fine silage, DCCS = dry corn and coarse silage.

²SED = Standard error of difference.

³RFC = Ruminally fermentable carbohydrate.

Table 7. Effects of level of ruminally fermentable carbohydrates and forage particle size on dry matter digestion kinetics.

Dependent variable	Treatments ¹					Statistical significance (<i>P</i> -value)		
	HMCFS	HMCCS	DCFS	DCCS	SED ²	RFC ³	Forage	RFC × Forage
Fraction, % of DM								
a	39.6	34.0	34.5	29.8	1.1	0.0001	0.0001	0.54
b	44.4	48.9	48.1	51.7	1.7	0.02	0.005	0.70
c	15.9	17.1	17.5	18.5	1.0	0.05	0.16	0.94
Lag, h	2.4	2.7	3.2	1.2	1.0	0.56	0.24	0.12
k _d , %/h	0.03	0.05	0.04	0.06	0.004	0.15	0.0001	0.57
ERD ⁴ , %	84.0	82.7	82.3	81.9	1.0	0.08	0.23	0.60

¹Treatments: HMCFS = High-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = Dry corn and fine silage, DCCS = dry corn and coarse silage.

²SED = Standard error of difference.

³RFC = Ruminally fermentable carbohydrate.

⁴Effective rumen degradability calculated using ruminal rate of passage of chromium mordanted straw (k₁): ERD = a + (b(k_d/(k_d + k₁))).

ruminal digestibility (**ERD**) of diet DM tended to be higher for HMC diets than for DC diets when calculated using the solid outflow rate found in the study. This was in agreement with the higher apparent total tract digestibility of DM observed for HMC diets compared with DC diets.

Microbial Yield

Urinary purine derivative excretion and microbial N production estimates are shown in Table 8. Daily excretion of the two purine derivatives, uric acid and allantoin, was not affected by level of RFC or forage particle size. However, total purine excretion increased when DC was replaced with HMC, as did absorption of microbial purines. Consequently, the calculated intestinal flow of microbial N increased by 49.7 g/d. Increasing the availability of ruminal fermentable energy in-

creased ruminal microbial protein synthesis. The estimated increase in microbial N supply did not result in an increase in milk protein percentage or protein yield. However, microbial N supply increased numerically when forage particle size was increased in HMC diets and decreased numerically when forage particle size was increased in DC diets (*P* = 0.11). As mentioned earlier, cows fed HMC increased starch intake when forage particle size was increased, whereas cows fed DC decreased starch intake when forage particle size was increased. These numerical differences in microbial N supply supports the tendency for a forage particle size and corn-grain moisture interaction effect on milk protein percentage.

The results presented here differ from the results reported by Agca and Broderick (1995), who found an increase in milk protein yield when they increased grain fermentability by replacing high-moisture corn

Table 8. Effects of level of ruminally fermentable carbohydrates and forage particle size on purine derivative excretion.¹

Dependent variable	Treatments ¹					Statistical significance (<i>P</i> -value)		
	HMCFS	HMCCS	DCFS	DCCS	SED ²	RFC ³	Forage	RFC × Forage
Urinary excretion								
Uric acid, mmol/d	41.0	79.9	41.6	41.0	23.3	0.31	0.26	0.26
Allantoin, mmol/d	418.2	394.8	387.0	375.2	39.1	0.74	0.37	0.53
Total, mmol/d	457.8	486.3	426.0	403.4	23.1	0.003	0.86	0.12
Absorption, ⁴ mmol/d	484.1	518.4	446.7	419.3	27.4	0.002	0.86	0.11
Microbial N supply, ⁴ g/d	352.0	376.9	324.7	304.9	19.7	0.002	0.86	0.11
g microbial N/kg DOMI, ⁵ g/kg	22.0	22.4	20.6	20.2	1.4	0.10	0.99	0.68

¹Treatments: HMCFS = high-moisture corn and fine silage, HMCCS = high-moisture corn and coarse silage, DCFS = dry corn and fine silage, DCCS = dry corn and coarse silage.

²SED = standard error of difference.

³RFC = ruminally fermentable carbohydrate.

⁴Calculations based on equation from Chen and Gomes (1992).

⁵DOMI = digestible organic matter intake.

with ground high-moisture corn. However, all four diets in our study were high in CP, and protein was probably not limiting for milk production. Microbial yields in the present study were above the values reported by McCarthy et al. (1989), who used microbial purines in duodenal samples as a marker. The authors found microbial N yields of 286 g/d, in contrast to the 340 g/d found in this study, despite a similar intake of OM. Efficiency of microbial N production, expressed as grams of microbial N per kilogram of total tract digestible OM intake (**DOMI**) was not significantly affected by level of RFC, but tended to be higher for HMC than for DC ($P = 0.10$). This is likely related to a greater proportion of OM being digested in the rumen for HMC diets than for DC diets.

No effect of forage particle size on microbial N yield was found despite the lower ruminal pH for FS diets compared with CS diets (340.9 g N/d for CS vs. 338.4 g N/d for FS; see Krause et al., 2002 for ruminal pH results). A similar lack of relationship between ruminal pH and efficiency of microbial N production in vivo in both beef and dairy cattle was reported by Beauchemin et al. (2000). No depression in fiber utilization was found at the lower pH values in this study, which could explain the similar microbial N yield for FS and CS diets.

CONCLUSIONS

Dry matter intake was not affected by forage particle size, but increasing the level of ruminally fermentable carbohydrate in the diets by increasing corn moisture and changing processing decreased DMI. Decreasing forage particle size did not affect milk production, but increasing level of RFC tended to increase milk yield. This trend together with the lower DMI for cows fed high-moisture corn resulted in a higher efficiency of milk production for cows fed high-moisture corn compared with cows fed dry corn. No depression in milk fat occurred despite the small particle length of the forage, and both milk fat and protein percentage and yield were not affected by level of RFC or forage particle size. Feeding high-moisture corn increased total tract digestibility of DM, OM, and starch, compared with feeding dry corn, but fiber digestibility was unaffected by diet. Total purine excretion increased when level of RFC was increased and, consequently, the calculated intestinal flow of microbial N increased; however, this estimated increase did not result in an increase in milk protein percentage or yield. Forage particle size did not affect the estimated microbial protein yield.

Based on the results from this study, diets low in effective fiber and high in fermentable carbohydrates

can be fed to midlactation cows without causing negative effects on diet digestibility and cow productivity.

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