Pelleted Beet Pulp Substituted for High-Moisture Corn: 1. Effects on Feed Intake, Chewing Behavior, and Milk Production of Lactating Dairy Cows

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ABSTRACT

The effects of increasing concentrations of dried, pelleted beet pulp substituted for high-moisture corn on intake, milk production, and chewing behavior were evaluated using eight ruminally and duodenally cannulated multiparous Holstein cows in a duplicated 4×4 Latin square design with 21-d periods. Cows were 79 ± 17 (mean $\pm$ SD) d in milk at the beginning of the experiment. Experimental diets with 40% forage (corn silage and alfalfa silage) and 60% concentrate contained 0, 6.1, 12.1, or 24.3% beet pulp substituted for high-moisture corn on a dry matter basis. Diet concentrations of neutral detergent fiber (NDF) and starch were 24.3 and 34.6% (0% beet pulp), 26.2 and 30.5% (6% beet pulp), 28.0 and 26.5% (12% beet pulp), and 31.6 and 18.4% (24% beet pulp), respectively. Increasing beet pulp in the diet caused a linear decrease in dry matter intake (DMI). Time spent eating per day and per kilogram of DMI increased, and sorting against NDF tended to increase, with added beet pulp. Substituting beet pulp for corn caused a quadratic response in milk fat yield, with the highest yield for the 6% beet pulp treatment. A tendency was detected for a similar quadratic response in 3.5% fat-corrected milk yield. Lower plasma insulin concentration may have resulted in lower body condition gain for cows fed diets with higher beet pulp concentration. Partial substitution of pelleted beet pulp for high-moisture corn decreased intake but also may have permitted greater fat-corrected milk yield.

(Key words: beet pulp, high-moisture corn, milk yield, ruminal fill)

Abbreviation key: BP = beet pulp, 0BP = 0% beet pulp treatment, 6BP = 6% beet pulp treatment, 12BP = 12% beet pulp treatment, 24BP = 24% beet pulp treat-

ment, HMC = high-moisture corn, INDF = indigestible NDF, pdNDF = potentially digestible NDF.

INTRODUCTION

Grain is often substituted for forage in diets for high-producing cows in an effort to increase intake and milk yield. Reducing dietary NDF concentration by decreasing the forage-to-concentrate ratio usually increases DMI, probably by reducing the filling effect of the diet (Allen, 2000). However, increasing dietary starch can also negatively affect feed intake and milk production. Feeding less forage NDF reduces chewing (Allen, 1997), which can reduce flow of saliva and its buffers into the rumen. This could possibly reduce ruminal pH, fiber digestion, and milk fat concentration. Propionate production can increase with greater dietary starch content and can depress DMI (Anil and Forbes, 1980), limiting milk synthesis.

Adding nonforage NDF to low-forage diets might reduce the negative effects of increased starch fermentation without increasing the filling effect of the diet to the same extent as forage NDF. The responses of DMI to various nonforage fiber sources substituted for grain are not consistent (Allen, 2000). Beet pulp contains approximately 40% NDF and is unique in its high concentration of neutral-detergent soluble fiber, especially pectic substances. Previous experiments have reported a variety of responses in DMI to the substitution of dried beet pulp for corn grain. Of four experiments that substituted beet pulp for grain in a TMR, two reported increased DMI (Clark and Armentano, 1997; O'Mara et al., 1997), one reported decreased DMI (Mansfield et al., 1994), and one measured no effect of beet pulp on DMI (Swain and Armentano, 1994). Among the same experiments, three reported no effects of treatment on milk yield (Mansfield et al., 1994; Swain and Armentano, 1994; Clark and Armentano, 1997), and one reported decreased milk yield when beet pulp was substituted for corn grain (O'Mara et al., 1997). Fat-corrected milk yield, when reported, was not affected by treatment. In these experiments, beet pulp comprised at

Received November 12, 2002.

Accepted March 3, 2003.

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Table 1. Nutrient composition of high-moisture corn and dried, pelleted beet pulp.

Nutrient	High-moisture corn	Beet pulp
DM, % as fed	71.5	84.9
	% of DM	
NDF	10.0	39.9
CP	8.3	8.9
Indigestible NDF	3.8	8.0
Starch	70.5	3.9
Ether extract	4.7	0.7
Ash	1.0	7.8

least 15% of diet DM. However, the effects of rate of substitution and the mechanisms of intake regulation for diets containing beet pulp have not previously been investigated.

Substituting beet pulp for high-moisture corn in a diet with a low forage content should maximize DMI and 3.5% FCM yield at one or more rates of inclusion. Therefore, this experiment investigated the responses to four concentrations of beet pulp substituted for high-moisture corn (0, 6, 12, and 24% of diet DM) for feed intake, meal patterns, chewing behavior, ruminal nutrient pools, and milk yield and composition.

MATERIALS AND METHODS

This paper is the first of three papers in a series from one experiment that evaluated effects of the substitution of dried, pelleted beet pulp for high-moisture corn. This paper discusses treatment effects on feed intake and milk production, and the companion papers focus on digestion (Voelker and Allen, 2003a) and ruminal fermentation, including efficiency of microbial nitrogen production (Voelker and Allen, 2003b). Experimental procedures were approved by the All University Committee on Animal Use and Care at Michigan State University.

Cows and Treatments

Eight multiparous Holstein cows (79 ± 17 DIM; mean $\pm$ SD) from the Michigan State University Dairy Cattle Teaching and Research Center were assigned randomly to a duplicated 4×4 Latin square balanced for carryover effects in a dose-response arrangement of treatments. Treatments were diets containing dried, pelleted beet pulp (**BP**) at 0, 6, 12, and 24% substituted for high-moisture corn (**HMC**) on a DM basis. Treatment periods were 21 d, with the final 10 d used to collect samples and data. Cows were cannulated ruminally and duodenally prior to calving and assigned randomly to treatment sequence. Surgery was performed at the Department

of Large Animal Clinical Science, College of Veterinary Medicine, Michigan State University. At the beginning of the experiment, empty BW (ruminal digesta removed) of cows was 516 ± 64 kg (mean $\pm$ SD).

Nutrient composition for HMC and BP are shown in Table 1. Experimental diets contained 40% forage (50:50 corn silage: alfalfa silage), HMC, BP at 0 (**0BP**), 6 (**6BP**), 12 (**12BP**), and 24% (**24BP**) of diet DM, a premixed protein supplement (soybean meal, corn distiller's grains, and blood meal), and a mineral and vitamin mix (Table 2). All diets were formulated for 18% dietary CP and fed as TMR.

Data and Sample Collection

Throughout the experiment, cows were housed in tie stalls and fed once daily (1100 h) at 110% of expected intake. Amounts of feed offered and orts were weighed for each cow daily. Samples of all diet ingredients (0.5 kg) and orts from each cow (12.5%) were collected daily on d 12 to 19 and combined into one sample per period. Cows were milked twice daily in their stalls during the feeding behavior monitoring phase (d 16 to 19) and in a milking parlor during the rest of each period. Milk yield was measured, and milk was sampled, at each milking on d 16 to 19. Empty BW was measured after evacuation of ruminal digesta on the day immediately before the start of the first period, and on d 21 of each period. Body condition score was determined on the same days by three trained investigators blinded to treatments (Wildman et al., 1982; five-point scale where 1 = thin and 5 = fat).

Feeding behavior was monitored from d 16 to 19 (96 h) of each period by a computerized data acquisition system (Dado and Allen, 1993). Data of chewing activities, feed disappearance, and water consumption were recorded for each cow every 5 s. When chewing equipment malfunctioned for an individual cow during a 24-h period (1100 to 1100 h), chewing behavior was deleted for that cow during that 24-h period. The system successfully collected 83.1% of the total chewing behavior data (average 3.4 d per cow per period). Daily means were calculated for number of meal bouts per day, interval between meals, meal size, eating time, ruminating time, and total chewing time. These response variables were calculated as daily means, then averaged over the 4 d for each period.

Blood was collected from a coccygeal vessel into tubes containing sodium heparin every 9 h from d 12 to 14, starting at 1400 h on d 12, so that samples represented 3-h intervals of a 24-h period in order to account for diurnal variation. Blood was centrifuged at $2000 \times g$ for 15 min immediately after sample collection, and

Table 2. Ingredient and nutrient composition of experimental diets.

	0% BP	6% BP	12% BP	24% BP
Ingredients	% of DM			
Corn silage ¹	20.1	20.1	20.1	20.1
Alfalfa silage ²	19.9	19.9	19.9	19.9
Protein mix ³	19.5	19.5	19.5	19.5
Mineral vitamin mix ⁴	4.8	4.8	4.8	4.8
Dried, pelleted beet pulp	0	6.1	12.1	24.3
High-moisture corn	35.6	29.5	23.5	11.4
Nutrient				
DM	50.2	50.5	50.8	51.6
Starch	34.6	30.5	26.5	18.4
NDF	24.3	26.2	28.0	31.6
Indigestible NDF	9.4	9.6	9.8	10.2
Forage NDF	17.1	17.1	17.1	17.1
CP	18.0	18.0	18.0	18.1
Rumen-undegraded CP ⁵	11.6	11.4	11.3	10.9
% Starch from high-moisture corn	72.7	68.3	62.6	43.7
% NDF from forage	70.2	65.3	61.1	54.1
% NDF from beet pulp	0.0	9.3	17.3	30.7

¹Corn silage contained 36.2% DM (as fed) and (DM basis) 43.5% NDF, 7.6% CP, 13.4% indigestible NDF, 28.5% starch, and 3.8% ash.

²Alfalfa silage contained 34.6% DM (as fed) and (DM basis) 41.8% NDF, 19.5% CP, 26.1% indigestible NDF, 3.0% starch, and 8.1% ash.

³Protein mix contained 75% soybean meal, 20% corn distillers grains (with solubles), and 5% blood meal.

⁴Mineral vitamin mix contained 10.4% trace mineral premix, 0.4% vitamin D, 0.4% vitamin A, 2.7% magnesium oxide, 22.3% dicalcium phosphate, and 63.8% dry ground corn as a carrier.

⁵Rumen-degraded protein estimated using values from NRC (2001).

plasma was harvested and frozen at -20°C until analysis.

Ruminal contents were evacuated manually through the ruminal cannula at 1500 h (4 h after feeding) on d 20 and at 0900 h (2 h before feeding) at end of d 21 of each period. Total ruminal content mass and volume were determined. During evacuation, 10% aliquots of digesta were separated to allow accurate sampling. Aliquots were squeezed through a nylon screen (1-mm pore size) to separate into primarily solid and liquid phases. Samples were taken from both phases to determine nutrient pool size, and additional liquid samples were taken to measure VFA concentration and rumen fluid consistency. All samples except the consistency sample were frozen immediately at -20°C .

Sample and Statistical Analysis

Diet ingredients and orts were dried in a 55°C forced-air oven for 72 h and analyzed for DM concentration. All samples were ground with a Wiley mill (1-mm screen; Authur H. Thomas, Philadelphia, PA). Rumen liquid and solid subsamples were lyophilized (Tri-Philizer MP, FTS Systems, Stone Ridge, NY), ground, and recombined according to the original ratio of solid and liquid DM. Samples were analyzed for ash, NDF, indigestible NDF (**INDF**), CP, and starch. Ash concentration was determined after 5 h of oxidation at 500°C in

a muffle furnace. Concentrations of NDF were determined according to Van Soest et al. (1991, method A). Indigestible NDF was estimated as NDF residue after 120-h in vitro fermentation (Goering and Van Soest, 1970). Rumen fluid for the in vitro incubations was collected from a nonpregnant dry cow fed only alfalfa hay. Fraction of potentially digestible NDF (**pdNDF**) was calculated by difference ($1.00 - \text{INDF}$). Forage samples were analyzed for ADF and sulfuric acid lignin content (Van Soest et al., 1991). Crude protein was analyzed according to Hach et al. (1987). Starch was measured by an enzymatic method (Karkalas, 1985) after samples were gelatinized with sodium hydroxide. Glucose concentration was measured using a glucose oxidase method (Glucose kit #510; Sigma Chemical Co., St. Louis, MO), and absorbance was determined with a micro-plate reader (SpectraMax 190, Molecular Devices Corp., Sunnyvale, CA). Concentrations of all nutrients except DM were expressed as percentages of DM determined by drying at 105°C in a forced-air oven for more than 8 h.

A commercial kit was used to determine plasma concentration of insulin (Coat-A-Count, Diagnostic Products Corporation, Los Angeles, CA), glucose (Glucose kit #510; Sigma Chemical Co.), NEFA (NEFA C-kit; Wako Chemicals USA, Richmond, VA), and β -hydroxybutyrate (**BHBA**; kit #310-A; Sigma Chemical Co.). Milk samples were analyzed for fat, true protein, and

lactose with infrared spectroscopy by Michigan DHIA (East Lansing).

Energy values were calculated as follows:

$NE_L \text{ intake} = \text{DMI (kg)} \times (0.0245 \times \text{TDN}(\%))$ (NRC, 1989) [OM digestibility for calculation of TDN was measured as reported in Voelker and Allen (2003a)];

$\text{Milk } NE_L \text{ (Mcal/kg)} = 0.0929 \times (\text{Fat } \%) + 0.0563 \times (\text{True Protein}\%) + 0.0395 \times (\text{Lactose}\%)$ (NRC, 2001);

$\text{Milk } NE_L \text{ (Mcal/d)} = \text{MY (kg)} \times [0.0929 \times (\text{Fat } \%) + 0.0563 \times (\text{True Protein}\%) + 0.0395 \times (\text{Lactose}\%)]$ (NRC, 2001);

$NE_M = 0.080 \times BW^{0.75}$ (NRC, 2001);

and $NE_L \text{ balance} = NE_L \text{ intake} - NE_M - NE_L \text{ (Mcal/d)}$.

Ruminal pool sizes (kg) of OM, NDF, INDF, and starch were determined by multiplying the concentration of each component in DM by the ruminal digesta DM weight (kg).

Hunger and satiety ratios were calculated as follows (Forbes, 1995):

Hunger ratio = meal kg DM/premeal interval; and

Satiety ratio = meal kg DM/postmeal interval.

Ratios were calculated for individual meals and averaged for the 4 d of feeding behavior data collection.

All data were analyzed using the fit model procedure of JMP (Version 4, SAS Institute, Cary, NC) according to the following model:

$$Y_{ijk} = \mu + C_i + P_j + T_k + e_{ijk},$$

where

μ = overall mean,
 C_i = random effect of cow ($i = 1$ to 8),
 P_j = fixed effect of period ($j = 1$ to 4),
 T_k = fixed effect of treatment ($k = 1$ to 4),
 e_{ijk} = residual, assumed to be normally distributed.

Period $\times$ treatment interaction was originally evaluated, but it was removed from the statistical model because it was not significant for response variables of primary interest. Linear and quadratic dose-response effects were evaluated using the same model with diet percent BP (0, 6, 12, and 24%) in place of the fixed effect

of treatment. Pearson correlation coefficients were determined between cow-period observations for some parameters. Treatment effects, linear and quadratic responses, and correlations were declared significant at $P < 0.05$, and tendencies were declared at $P < 0.10$.

Data from two cow-periods were excluded from statistical analysis. One cow developed a cecal torsion requiring surgery early in period 3; data and samples were not collected from this cow during period 3, but she recovered sufficiently for her period 4 data to be used. Period 4 data from a second cow were excluded after she showed signs of estrus during the collection period because her feed intake and milk yield were outliers (outside the 95% confidence interval for cow-period observations).

RESULTS AND DISCUSSION

Feed Intake

As beet pulp was increasingly substituted for high-moisture corn, DMI decreased ($P < 0.05$; Table 3). Although the relationship detected was linear, DMI was similar for 0BP, 6BP, and 12BP, and DMI was numerically lower by approximately 2 kg/d for 24BP. Others have reported varied responses in DMI to substitution of BP for corn grain. Swain and Armentano (1994) reported no DMI effect. Substituting BP at 16% of DM into a high-corn diet (Clark and Armentano, 1997) increased intake by only 0.4 kg/d, while replacing half of the corn with BP in a higher-forage diet (Mansfield et al., 1994) reduced intake by 1.3 kg/d. The diets fed in the latter experiment are the most similar to diets in the present study and had a DMI response similar to the numerical difference between 24BP and the other three treatments.

Regulation of Feed Intake

Intake can be affected by innumerable variables, such as ruminal fill, meal patterns, metabolic fuels, and ruminal patterns of fermentation and pH. Substituting a high-fiber byproduct for grain may have resulted in the limitation of intake by physical filling effects of the diet, but "fill" is likely a composite of several physical and chemical characteristics of the diet that affect volume and mass of digesta over time (Forbes, 1995). Because volume and mass of wet ruminal contents did not decrease when DMI decreased with increasing dietary BP (Table 3), stimulation of stretch receptors in the rumen wall probably was a predominant factor signaling satiety and reducing DMI with added BP. Water content of ruminal digesta increased linearly as BP was substituted for HMC ($P = 0.01$), probably because BP has a higher water-holding capacity than grains and other

Table 3. Effects of substitution of pelleted beet pulp for high-moisture corn on nutrient intake and ruminal pool.

	Treatment LS means ¹					P ²		
	0% BP	6% BP	12% BP	24% BP	SE	Trt	L	Q
Intake, kg/d								
DM	24.8	25.0	25.1	22.9	0.8	0.11	<0.05	0.13
OM	22.3	22.4	22.4	20.2	0.7	0.06	0.50	0.15
NDF	5.7	6.2	6.6	6.9	0.2	<0.01	0.01	0.15
Starch	8.2	7.3	6.4	4.0	0.2	<0.01	<0.01	0.21
Ruminal wet contents, kg	77.7	76.7	78.9	80.7	2.2	0.36	0.11	0.58
Ruminal contents volume, L	96.1	92.8	95.5	96.0	3.0	0.64	0.49	0.43
Ruminal contents, % DM	14.2	13.9	13.4	13.2	0.4	0.12	0.01	0.57
Ruminal pool, kg								
DM	11.0	10.4	10.6	9.9	0.5	0.19	0.04	0.74
OM	10.1	9.5	9.7	9.0	0.5	0.14	0.03	0.85
NDF	5.5	5.0	5.2	4.9	0.3	0.19	0.11	0.62
Potentially digestible NDF	2.4	2.1	2.3	2.1	0.2	0.30	0.17	0.61
Indigestible NDF	3.1	2.9	2.8	2.8	0.2	0.42	0.13	0.21
Starch	1.24	1.03	0.87	0.63	0.08	<0.01	<0.01	0.36

¹Treatments were beet pulp (BP) substituted for high-moisture corn as 0, 6, 12, and 24% of diet DM.

²Trt: treatment effect, L: linear effect, Q: quadratic effect.

byproducts, and similar to alfalfa and grass (Ramanzin et al., 1994; Bailoni et al., 1998). The substitution of BP for HMC probably increased the water-holding capacity of the digesta and contributed to the tendency for an apparent increase in digesta wet weight ($P = 0.11$). Neither ruminal DM pool nor ruminal NDF pool was limiting to intake, because DM pool decreased linearly ($P = 0.04$), and NDF pool appeared to decrease linearly ($P = 0.11$), as added BP reduced DMI. Therefore, ruminal digesta volume, weight, and water-hold-

ing capacity contributed to the limitation of intake by distension when HMC was replaced with BP.

Feed intake can be increased by reducing intermeal interval or by increasing meal size. Intermeal interval was not affected by treatment, nor was the amount of DM consumed per meal (Table 4). However, the response of hunger ratio (meal size/premeal interval) to BP substitution was quadratic ($P < 0.01$) and was greatest for 12BP and lowest for 24BP, suggesting that hunger had the greatest effect on intake for 12BP and the

Table 4. Effects of substitution of pelleted beet pulp for high-moisture corn on meal patterns and water consumption.

	Treatment LS means ¹					P ²		
	0% BP	6% BP	12% BP	24% BP	SE	Trt	L	Q
Meals/d	9.7	9.5	9.3	9.0	0.4	0.55	0.13	0.93
Meal length, min/meal	37.9	36.6	37.6	40.3	2.9	0.66	0.64	0.45
Meal size, kg								
DM	2.6	2.5	2.5	2.6	0.1	0.70	0.44	0.35
NDF	0.61	0.61	0.68	0.79	0.04	<0.01	<0.01	0.38
INDF	0.26	0.26	0.27	0.29	0.02	0.22	0.06	0.38
Starch	0.87	0.72	0.63	0.47	0.04	<0.01	<0.01	0.25
Intermeal interval, min	100	100	103	106	4	0.56	0.16	0.94
Eating chew rate, chews/min	73.4	73.5	74.6	74.7	2.8	0.65	0.63	0.86
Hunger ratio ³ , kg/min	0.16	0.19	0.20	0.14	0.02	0.03	0.01	<0.01
Satiety ratio ³ , kg/min	0.27	0.21	0.25	0.23	0.04	0.17	0.22	0.30
Rumination bouts/d	12.6	12.6	12.6	12.6	0.5	1.00	1.00	0.97
Ruminating bout length, min	36.6	37.6	38.9	38.6	2.4	0.66	0.33	0.48
Interval between ruminating bouts, min	70.4	71.2	67.6	67.5	2.7	0.45	0.18	0.95
Ruminating chew rate, chews/min	60.9	62.3	62.7	60.9	1.9	0.39	0.11	0.09
Drinking time, min/d	17	17	18	17	2	0.72	0.30	0.26
Water drunk, L/d	91	98	92	90	4	0.19	0.52	0.32
Drinking bouts/d	11	12	11	11	1	0.14	0.35	0.24

¹Treatments were beet pulp (BP) substituted for high-moisture corn as 0, 6, 12, and 24% of diet DM.

²Trt: treatment effect, L: linear effect, Q: quadratic effect.

³Hunger ratio = meal kg DM/premeal interval; Satiety ratio = meal kg DM/postmeal interval (Forbes, 1995).

Table 5. Effects of substitution of pelleted beet pulp for high-moisture corn on chewing time.

	Treatment LS means ¹					P ²		
	0% BP	6% BP	12% BP	24% BP	SE	Trt	L	Q
Eating time, min								
per d	298	297	302	318	13	0.21	0.04	0.44
per bout	34.0	33.0	33.7	36.6	2.7	0.65	0.65	0.45
per kg of DMI	12.0	11.9	12.2	13.4	0.5	0.03	<0.01	0.17
per kg of NDF intake	52.1	49.6	47.1	46.4	2.4	0.04	<0.01	0.27
per kg of forage NDF intake	74.1	73.2	74.7	83.1	3.0	0.02	<0.01	0.11
Feed NDF% – orts NDF %	1.0	1.6	3.8	2.2	2.0	0.15	0.07	0.12
Ruminating time, min								
per d	472	467	483	499	24	0.61	0.15	0.73
per bout	35.9	37.1	38.4	38.1	2.5	0.65	0.31	0.45
per kg of DMI	19.6	18.6	19.4	21.3	0.9	0.07	0.09	0.05
per kg of NDF intake	82.7	75.8	73.6	74.6	4.6	0.18	0.05	0.12
per kg of forage NDF intake	123	115	119	132	6	0.04	0.07	0.02
per kg ruminal DM pool	44.4	46.0	46.8	51.3	3.4	0.31	0.05	0.78
per kg ruminal NDF pool	89.2	98.0	93.3	104	8	0.28	0.13	0.94
Total chewing time, min								
per d	784	792	805	833	25	0.50	0.12	0.89
per bout	35.1	35.3	36.0	38.0	1.8	0.64	0.06	0.77
per kg of DMI	31.1	31.1	32.7	35.5	1.4	0.07	0.01	0.44
per kg of NDF intake	135	125	123	124	6	0.22	0.07	0.15
per kg of forage NDF intake	192	190	199	220	8	0.07	0.01	0.22
per kg ruminal DM pool	73.5	74.5	77.6	83.0	4.7	0.30	0.04	0.78
per kg ruminal NDF pool	148	159	154	168	11	0.36	0.12	0.87

¹Treatments were beet pulp (BP) substituted for high-moisture corn as 0, 6, 12, and 24% of diet DM.²Trt: treatment effect, L: linear effect, Q: quadratic effect.

least effect for 24BP. This quadratic response suggests that hunger eventually was counteracted by other factors limiting intake; cows might eat to minimize total discomfort resulting from both hunger and satiety signals (Forbes, 2000). Satiety ratio was unaffected by treatment ($P > 0.15$), but since hunger and satiety signals are integrated to regulate feed intake (Forbes, 1995), response of hunger ratio or satiety ratio alone cannot describe the mechanisms of intake regulation.

Across cow-period observations, DMI was not related to the number of meals per day, meal length, intermeal interval, or NDF consumed per meal (Table 6). As meal

size increased, DMI also increased (Figure 1a; $R = 0.39$, $P = 0.04$), although the correlation coefficient is not high. Hunger ratio was also positively correlated with DMI (Table 6), so the ability to consume a larger amount of feed at one meal, before satiety signals such as absorption of metabolic fuels or ruminal fill overcame hunger, increased the amount of feed consumed in the entire day. Average consumption of NDF per meal increased ($P < 0.001$) with added BP (Table 4), so increasing NDF consumption per meal may have slowed feed intake. However, as will be discussed further, eating rate and time probably did not actually limit daily DMI. Whereas dried, pelleted BP might be expected to physically affect eating behavior, eating chew rate was unaffected by treatment (Table 4).

Eating time per day and per kilogram of DMI increased linearly with added BP ($P = 0.04$, $P < 0.01$, respectively), so rate of feed intake was slowed (Table 5). Others have reported no effect of BP substitution for corn on time eating per day or per kilogram of DMI (Clark and Armentano, 1997). Across cow-period observations, greater time spent in total chewing per kilogram of DMI was associated with decreased DMI (Table 6). As diet NDF intake increased with added BP in the present experiment, time eating per kilogram of NDF decreased ($P < 0.01$). Because forage content was equal across treatments, physical or chemical effects of BP apparently had a negative effect on rate of feed intake.

Table 6. Pearson correlation coefficients between DMI and eating or chewing behavior.

	DMI, kg/d
Meals/d	0.10
Meal length, min	0.10
Intermeal interval, min	-0.34
Meal DM, kg/meal	0.39 ¹
Meal NDF, kg/meal	-0.02
Hunger ratio ² , kg/min	0.86 ¹
Time eating, min/d	0.21
Time eating/kg DMI	-0.34
Time eating/kg forage NDF intake	-0.38 ¹
Total chewing time (TCT), min/d	-0.01
TCT/kg DMI	-0.60 ¹
TCT/kg forage NDF intake	-0.68 ¹

¹Correlation is significant ($P < 0.05$).²Calculated for each meal: kg DMI/premeal interval (Forbes, 1995).

Figure 1. Relationship between DMI (kg/d) and (a) average kg DMI/meal (DMI = $16.3 + 2.8 \times \text{meal DMI}$; $R = 0.40$; $P < 0.04$); (b) mean ruminal pH ($R = 0.05$; $P > 0.70$); and (c) pH standard deviation (DMI = $27.1 - 11.5 \times \text{pH standard deviation}$; $R = -0.41$; $P < 0.03$). ○ denotes 0% beet pulp, + denotes 6% beet pulp, ■ denotes 12% beet pulp, and ● denotes 24% beet pulp (% diet DM) substituted for high-moisture corn.

Table 7. Pearson correlation coefficients between DMI and characteristics of ruminal fermentation and pH.

	DMI, kg/d
Total ruminal (VFA), mM	-0.23
% propionate, mol/100 mol VFA	-0.23
Acetate:propionate	0.19
Valerate absorption rate, %/h	0.33
Ruminal pH mean	0.07
Ruminal pH standard deviation	-0.42 ¹
Ruminal pH minimum	0.29
Ruminal pH range	-0.30
Ruminal pH variance	-0.42 ¹

¹Correlation is significant ($P < 0.05$).

Due to the physical form of pelleted BP, it is easily sorted. While sorting against BP was not measured, cows tended to increasingly sort against dietary NDF ($P = 0.07$) as the concentration of BP increased in the diet (Table 5). Therefore, sorting against NDF may have slowed intake. Although replacing HMC with BP tended to increase sorting and slowed rate of feed intake, time spent eating and in total chewing did not limit DMI. If eating time or total chewing time were limiting to DMI, then those responses should demonstrate a quadratic increase, increasing at a decreasing rate, as DMI was reduced with increasing dietary BP concentration, eventually reaching a plateau. Although linear responses were detected (Table 5), no quadratic responses were detected for time spent eating, ruminating, or in total chewing. Nor was time spent eating or in total chewing related to DMI across cow-period observations (Table 6). Therefore, eating and chewing time were not primary factors limiting feed intake.

Intake might be regulated by the metabolism of propionate in the liver (Allen, 2000), and ruminal propionate production is usually increased by greater starch fermentation. The amount of starch truly digested in the rumen decreased from 3.8 to 0.7 kg/d (Voelker and Allen, 2003a), and ruminal molar percent of propionate in total VFA decreased quadratically (Voelker and Allen, 2003b) as starch intake was reduced by approximately half (Table 3) and as true ruminal starch digestibility decreased from 46.5% to only 16.9% (Voelker and Allen, 2003a) with added BP. Therefore, it is not likely that propionate metabolism in the liver caused the reduction in DMI with added BP, because hepatic propionate oxidation probably decreased with added BP. In addition, across cow-period observations, DMI was not related to total VFA concentration, molar percent of propionate in total VFA, or acetate:propionate (Table 7). Therefore, ruminal VFA concentration and absorption rate did not negatively affect intake.

Ruminal pH might be implicated in the control of feed intake, particularly in satiety because VFA are

Table 8. Effects of substitution of pelleted beet pulp for high-moisture corn on milk production.

	Treatment LS means ¹					P ²		
	0% BP	6% BP	12% BP	24% BP	SE	Trt	L	Q
Yield, kg/d								
Milk	36.4	36.6	35.9	35.4	1.2	0.58	0.95	0.74
3.5% FCM ³	37.4	38.4	38.0	36.8	1.2	0.20	0.14	0.07
Milk fat	1.34	1.40	1.39	1.33	0.07	0.14	0.04	0.03
Milk protein	1.13	1.15	1.15	1.09	0.03	0.18	0.29	0.11
Milk lactose	1.80	1.82	1.78	1.75	0.07	0.57	0.99	0.71
Milk composition, %								
Fat	3.72	3.84	3.90	3.81	0.22	0.46	0.12	0.16
Protein	3.21	3.21	3.22	3.10	0.11	0.41	0.59	0.32
Lactose	4.95	4.96	4.95	4.94	0.02	0.75	0.66	0.53
kg 3.5% FCM/kg DMI	1.51	1.54	1.52	1.62	0.05	0.26	0.07	0.49

¹Treatments were beet pulp (BP) substituted for high-moisture corn as 0, 6, 12, and 24% of diet DM.

²Trt: treatment effect, L: linear effect, Q: quadratic effect.

³3.5% fat-corrected milk.

absorbed faster in the undissociated form at lower pH. Ruminal pH was measured over 96 h and is reported in a companion paper (Voelker and Allen, 2003b). Substituting BP for HMC decreased DMI and resulted in a range of individual mean daily pH values between 5.58 and 6.56, but the decrease in DMI with added BP was not accompanied by a decrease in mean ruminal pH (Voelker and Allen, 2003b), and mean pH and DMI were not correlated across cow-period observations (Figure 1b). Intake was not correlated with daily range, maximum, or minimum pH, but DMI was negatively related to daily standard deviation (Figure 1c; $R = -0.41$, $P = 0.03$) and variance ($R = -0.42$, $P = 0.03$) of ruminal pH. The direction of cause and effect is not established by these results. Increased intake might be associated with reduced pH variation if cows consumed more frequent, smaller meals and thus increased intake while reducing ruminal pH variation. However, increased DMI was associated with greater meal size, not smaller meal size (Figure 1a), and DMI was not related to intermeal interval, so it is unlikely that the consumption of more frequent, smaller meals resulted in increased DMI and decreased ruminal pH variation. Rather, it is more likely that increased pH fluctuations resulted in feed intake depression. Increases in both DMI and daily pH range were associated with the higher starch diets (Table 3; and in Voelker and Allen, 2003b), so the negative correlation between DMI and ruminal pH variation is independent of the treatment effects.

Thus, feed intake was affected by both treatment-dependent and treatment-independent factors. The limitation of intake by ruminal distention was closely related to effects detected among treatment means as BP was substituted for HMC. By contrast, the relationship between pH variation and DMI occurred independently from treatment effects for the individual variables.

Milk Production and Nutrient Partitioning

Milk yield was not affected by diet ($P > 0.50$; Table 8), but increasing BP tended to have a quadratic effect ($P = 0.07$) on 3.5% FCM yield and had a quadratic effect on milk fat yield ($P = 0.03$). Yields of FCM and milk fat were highest for 6BP and lowest for 24BP. These effects correspond to nonsignificant quadratic patterns of raw milk yield and milk fat content in response to increasing BP and decreasing HMC, and they may reflect a slight response in milk lactose and fat synthesis to added BP at the lower concentrations. Lower FCM yield for 24BP is likely because of decreased DMI. Three of four other experiments comparing corn grain with BP in TMR reported no effect of treatment on raw milk yield (Mansfield et al., 1994; Swain and Armentano, 1994; Clark and Armentano, 1997), and those that reported FCM yield found no effect of diet (Mansfield et al., 1994; Clark and Armentano, 1997). Only one experiment (O'Mara et al., 1997) found a 1.4-kg/d decrease in raw milk yield when BP was substituted for corn in a grass-silage-based diet. Milk protein and lactose yields and concentrations were not affected in the present experiment by substituting BP for HMC (Table 8). The reduction in DMI with increasing BP was greater than the decrease in milk yield, so the efficiency of milk production (kg FCM/kg DMI) tended to increase ($P = 0.07$) as HMC decreased and BP increased in the diet.

Beginning with a diet containing 36% HMC and 35% starch, then substituting BP containing 40% NDF for the HMC not only served to test the treatment effects of two common feed ingredients; it also provided a large pool of data including variables such as intake, production, energy status, and feeding behavior, with reasonably wide ranges, under identical conditions. Relationships among these variables across cow-period observations help both to interpret treatment effects and to

Table 9. Effects of substitution of pelleted beet pulp for high-moisture corn on energy balance, and plasma insulin, NEFA, and β -hydroxybutyrate.

	Treatment LS Means ¹					P ²		
	0% BP	6% BP	12% BP	24% BP	SE	Trt	L	Q
NE _L intake ³ , Mcal/d	39.8	39.2	41.0	37.4	1.2	0.21	0.38	0.21
Milk NE _L ⁴ , Mcal/kg	0.72	0.73	0.74	0.72	0.02	0.50	0.13	0.13
Milk NE _L , % NE _L intake	65.9	67.5	64.9	68.9	1.8	0.28	0.66	0.42
BW change, kg/21 d	-8.0	6.7	-11.6	-1.5	15.8	0.49	0.50	0.45
BCS change/21 d	0.06	0.11	-0.04	-0.05	0.06	0.15	0.06	0.93
NE _L balance ⁵ , Mcal/d	4.0	2.9	4.9	2.1	0.9	0.13	0.54	0.33
NE _{Maint} , %NE _L intake	24.3	24.4	22.9	25.5	0.9	0.17	0.19	0.11
Meal plasma insulin ⁶ , μ IU/ml	13.0	13.2	11.6	8.9	1.2	<0.01	<0.01	0.26
Plasma insulin standard deviation ⁶ , μ IU/ml	4.9	4.7	3.8	2.9	0.5	0.02	<0.01	0.96
Plasma glucose ⁷ , mg/dl	58.4	59.8	58.2	56.5	1.0	0.08	0.06	0.17
Plasma glucose:insulin, mg/ μ IU	4.75	4.73	5.44	6.48	0.51	0.02	0.002	0.46
Plasma NEFA ⁷ , mM	60.6	58.3	64.0	59.5	3.9	0.69	0.65	0.64
Plasma β -hydroxybutyrate ⁷ , (mg/dl)	5.85	5.42	6.50	6.34	0.44	0.20	0.18	0.93

¹Treatments were beet pulp (BP) substituted for high-moisture corn as 0, 6, 12 and 24% of diet DM.

²Trt: treatment effect, L: linear effect, Q: quadratic effect.

³NE_{L(intake)} = DMI (kg) $\times$ (0.0245 $\times$ TDN(%)) (NRC, 1989).

⁴NE_{L(milk)} (Mcal/d) = MY (kg) $\times$ (0.0929 $\times$ fat% + 0.0563 $\times$ true protein% + 0.0395 $\times$ lactose%) (NRC, 2001).

⁵NE_{L(intake)} - NE_{L(maintenance)} - NE_{L(milk)}, where NE_{L(maintenance)} = 0.080 $\times$ BW^{0.75} (NRC, 2001).

⁶Calculated using eight samples collected over 3 d, representing 3-h intervals of a 24-h day.

⁷Measured for a composite of eight samples collected over 3 d, representing 3-h intervals of a 24-h d.

clarify basic scientific principles of intake, milk production, and feeding behavior in ruminants. Among cow-period observations, increasing ruminal pH (Voelker and Allen, 2003b) was associated with greater yield of FCM ($R = 0.43$, $P = 0.03$) and tended to be associated with greater fat yield, but pH was not related to milk fat content ($P > 0.50$).

Although intake and milk production were influenced by diet, measures of energy intake, energy partitioning to milk and output in milk, and energy balance were not affected (Table 9); nor were changes in BW different among treatments ($P > 0.45$). Whereas partitioning of absorbed energy to milk (milk NE_L as a percent of NE_L intake) was not affected by adding BP, a linear tendency ($P = 0.06$) was detected for a slightly more negative change in BCS; as BP replaced HMC in the diets, cows likely mobilized nutrients from body reserves for milk production, rather than adding condition as they did for 0BP and 6BP.

Plasma β -Hydroxybutyrate

The concentration of BHBA in blood plasma was not different across treatments (Table 9). Plasma BHBA was not correlated with the concentration of butyrate in rumen fluid ($P > 0.85$) but was positively correlated with the ruminal pool (mol) of butyrate ($R = 0.46$, $P = 0.01$) and tended to be positively correlated with the molar proportion of butyrate in total ruminal VFA ($R = 0.34$, $P = 0.07$). Plasma BHBA concentration was also positively correlated with milk fat yield ($R = 0.37$, $P =$

0.04) and tended to be positively correlated with both 3.5% FCM yield ($R = 0.34$, $P = 0.07$) and milk fat concentration ($R = 0.32$, $P = 0.09$). This suggests that increased availability of BHBA, and its precursors or products, as metabolic fuel may have permitted increased milk fat synthesis.

Plasma Insulin, Glucose, and NEFA

Plasma insulin responds to energy intake, especially glucose and its precursors, and it both regulates and is regulated by energy utilization in various tissues, including liver, muscle, adipose, and mammary tissue. As cows consumed more BP and less HMC, both plasma insulin concentration and the standard deviation of insulin concentration over 24 h decreased (Table 9). A linear decrease was detected for both mean ($P < 0.001$) and standard deviation ($P < 0.01$) of plasma insulin as BP increased. Plasma glucose concentration tended to decrease linearly with added BP ($P = 0.06$). As might be expected, plasma glucose concentration was positively correlated with plasma insulin concentration among cow-period observations (Table 10). Plasma glucose:insulin increased with added BP ($P < 0.05$; Table 9), indicating that the relationship between glucose and insulin concentration was affected by treatment. However a cause-effect relationship cannot be determined.

The tendency for a more negative BCS change with added BP (Table 9) might be caused by the corresponding decreases in DMI, plasma glucose, or plasma insulin concentration in response to BP. However, among cow-

Table 10. Pearson correlation coefficients between plasma insulin concentration and characteristics of intake, production, and energy balance.

	Plasma insulin ¹ , μ IU/ml
Plasma glucose ² , mg/dl	0.45 ³
DMI, kg/d	0.41 ³
Total tract starch digested, kg/d	0.51 ³
Milk NE _L , Mcal/kg	0.51 ³
Milk NE _L , %NE _L intake	-0.27

¹Calculated using eight samples collected over 3 d, representing 3-h intervals of a 24-h day.

²Measured for a composite of eight samples collected over 3 d, representing 3-h intervals of a 24-h day.

³Correlation is significant ($P < 0.05$).

period observations, DMI, plasma insulin, plasma glucose, and plasma glucose:insulin were not related to change in BCS (data not shown). Insulin secretion affects metabolism of adipose tissue, and plasma concentration of NEFA, a product of adipose catabolism, tended to be negatively related to plasma insulin concentration ($R = -0.36$, $P = 0.07$). However, plasma NEFA concentration was not affected by treatment (Table 9) and was not related to change in BCS (data not shown). Thus, the mechanism for the BCS effect of treatment is not clear.

Insulin secretion can be affected by intake, ruminal fermentation products, and absorption of metabolites throughout the gastrointestinal tract. Because both DMI and plasma insulin decreased with added BP, lower feed intake might have resulted in lower insulin, although NE_L intake was not affected by treatment (Table 9). Insulin concentration and DMI were correlated across treatments as well (Table 10; $R = 0.41$, $P = 0.03$). Starch consumed per meal decreased as BP increased (Table 3), so a smaller amount of starch from HMC was undergoing rapid fermentation during and immediately after each meal, and amount and fluctuation of propionate flux to the liver was likely decreased, possibly reducing variation in plasma glucose concentration. While variation of propionate flux and plasma glucose were not measured, plasma glucose concentration was positively correlated with ruminal propionate concentration ($R = 0.48$, $P < 0.01$). Lower fluctuation of plasma glucose likely resulted in lower plasma insulin concentration and less fluctuation in insulin concentration (Table 9), with the resulting decrease in energy partitioned to adipose tissue indicated by the tendency for decreased BCS.

Insulin secretion is also stimulated by increased plasma glucose concentration. Although there is little net glucose absorption across the portal-drained viscera in cattle (Reynolds, 1995), plasma glucose concentration may be increased by greater gluconeogenesis and

by greater availability of glucose-sparing fuels such as acetate, BHBA, and lactate. It can also be increased by greater glucose absorption and utilization in small intestine cells; most of the glucose absorbed in the ruminant small intestine probably is either utilized within intestinal cells, thus sparing circulating glucose, or is absorbed into blood as lactate, which can be used for gluconeogenesis. Although plasma insulin and glucose concentrations decreased with added BP, the amount of starch digested postruminally (kg/d) was not different among treatments (Voelker and Allen, 2003a); and among cow-period observations, amount or proportion of starch digested postruminally was not related to insulin concentration, so intestinal glucose or lactate absorption alone probably did not contribute to the insulin effect. Only the amount of starch consumed or digested in the whole tract was related to plasma insulin ($R = 0.51$, $P < 0.01$; and $R = 0.52$, $P < 0.01$, respectively), and adding ruminal digestibility of starch to the model did not improve the prediction of insulin concentration from starch intake. Therefore, although replacing HMC with BP shifted starch digestion from the rumen to the intestines, the reduced plasma insulin and glucose concentrations with added BP probably were caused by the reduction in the total amount of starch consumed and digested, regardless of the form in which it was absorbed.

SUMMARY

Substitution of dried, pelleted beet pulp for high-moisture corn resulted in decreased DMI, and ruminal distention probably limited DMI with added beet pulp. Mean and minimum ruminal pH did not affect DMI, but, independent of treatment effects, increased variation in pH might have decreased DMI. Replacing high-moisture corn with beet pulp caused a quadratic response for milk fat yield and the tendency for a quadratic response for FCM yield. Partial substitution of pelleted beet pulp for high-moisture corn decreased intake due to filling effects but also permitted similar or greater FCM yield. Beet pulp tended to increase the efficiency of conversion of feed to milk and can be partially substituted for high-moisture corn depending on their relative costs and value of milk produced.

ACKNOWLEDGMENTS

The authors wish to thank D. G. Main, R. A. Longuski, Y. Ying, M. Oba, C. S. Mooney, R. A. Kreft, and the staff of the Michigan State University Dairy Cattle Teaching and Research Center for their assistance in this experiment.

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