Effect of straw particle size on the behavior, health, and production of early-lactation dairy cows

R. E. Coon,* T. F. Duffield,† and T. J. DeVries*¹

*Department of Animal Biosciences, and

†Department of Population Medicine, University of Guelph, Guelph, Ontario, N1G 2W1, Canada

ABSTRACT

The objective of this study was to determine the effect of reducing the particle size of wheat straw in a total mixed ration (TMR) on cow behavior, health, and production in early lactation. For 28 d after calving, 41 multiparous Holstein cows were individually provided either 1 of 2 TMR with 9% wheat straw (dry matter basis) chopped (1) using a 2.54-cm screen (short; $n = 21$) or (2) using a 5.08-cm screen (long; $n = 20$). Cows were housed in freestall pens during both the dry and lactating period. Enrollment in the trial was on a rolling basis and cows were evenly distributed by parity and milk production between treatments. Wireless telemetry boluses were used to measure reticulorumen pH. Automated systems recorded TMR dry matter intake, milk yield, and rumination activity. The TMR and orts samples were collected every 3 d to determine feed sorting. A particle separator was used to separate feed samples into 4 fractions: long (>19 mm), medium (<19 mm, >8 mm), short (<8 mm, >4 mm), and fine (<4 mm) particles. Feed sorting was calculated as actual intake of each particle fraction expressed as a percentage of its predicted intake. Cows sorted the longest TMR particles differently by treatment; on the long treatment cows sorted against long particles ($94.2 \pm 1.9\%$), whereas on the short treatment cows did not sort for or against these particles ($99.7 \pm 1.9\%$). Data were analyzed in mixed-effect linear regression models and fitted with polynomial functions over the 28 d of observations. The fitted data indicated treatment differences in linear coefficients, quadratic coefficients, and cubic coefficients for mean time (min/d) below a reticulorumen pH of 5.8 and milk yield. Rumination time (min/d) differed between treatments for quadratic and cubic coefficients. Cows on the short treatment linearly increased in dry matter intake at a greater rate than cows on the long treatment. Mean reticulorumen

pH decreased at a greater rate for cows on the long treatment than for cows on the short, as indicated by differences between linear coefficients. Cows on the short treatment tended to produce 75 kg more milk cumulatively during the first 28 d in milk than cows on long treatment. These results suggest that cows fed a diet with longer straw particles selected against physically effective fiber, which may have contributed to greater fluctuations in rumination time, reticulorumen pH, dry matter intake, and milk production in early lactation.

Key words: dairy cow, sorting, pH, rumination, straw

INTRODUCTION

When provided a TMR, dairy cows often sort their feed, typically favoring small grain components and avoiding longer forage particles (Leonardi and Armenitano, 2003; Leonardi et al., 2005a; DeVries et al., 2007). Particle size of forages is one of the primary factors influencing feed sorting, with smaller particles being less easily sorted than longer particles (Miller-Cushon and DeVries, 2017). Additionally, high palatability of the concentrate components of the TMR motivates cows to sort in favor of these smaller components and against the longer forage ingredients (Nombekela et al., 1994; Miller-Cushon and DeVries, 2017).

Intake of dietary forage is important, as it primarily contributes the physically effective NDF (peNDF) portion of the diet, which is responsible for stimulating rumination and improving fiber digestibility (Yang and Beauchemin, 2006a,b; Zebeli et al., 2012). Sorting behavior can result in an over-consumption of easily fermented carbohydrates and an under-consumption of peNDF (Miller-Cushon and DeVries, 2017). This unbalanced diet, as a result of sorting, may lead to an increased risk of SARA (DeVries et al., 2008); an overconsumption of grains relative to peNDF can cause a buildup of VFA and a resultant prolonged depression of the rumen pH (<5.6 – 5.8 for multiple hours per day) characteristic of SARA (Steele et al., 2016). Subacute ruminal acidosis can lead to decreased DMI,

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¹Corresponding author: tdevries@uoguelph.ca

milk production, and fiber digestibility (Plaizier et al., 2008). Fresh cows are especially vulnerable to SARA because of the abrupt transition from a low-energy diet to a more highly fermentable diet at calving (Steele et al., 2016). It is important that transition cows are not able to easily sort their feed during this time, as this behavior likely exacerbates the condition through over consumption of easily fermented carbohydrates and under consumption of effective fiber.

Nutritional management of fresh cows can be difficult because there are competing demands for nutrient-dense concentrate components to sustain lactation and for sufficient forage to maintain good rumen function. It is important that the dietary fiber in the diet be presented in a manner that discourages sorting to ensure a balanced diet that stimulates rumination. Reducing the particle size of the forage sources increases NDF intake and decreases sorting against the long particles and for fine particles (Miller-Cushon and DeVries, 2017). A forage particle size that is large enough to stimulate rumination, yet small enough to prevent sorting against the forage component may, thus, reduce the risk of SARA in early-lactation dairy cows.

The objective of our research was to determine if reducing the particle size of wheat straw in a diet for early-lactation cows would have positive effects on cow behavior, health, and production. We hypothesized that a diet with a smaller particle size wheat straw would minimize sorting behavior while maintaining DMI levels and rumination, resulting in a stabilization of reticulorumen pH.

MATERIALS AND METHODS

Animals and Housing

Forty-one multiparous Holstein cows (parity = 2.8 ± 1.1 postcalving; mean $\pm$ SD) were used in this study, which took place at the University of Guelph Livestock Research and Innovation Centre Dairy Facility (Elora, Ontario, Canada). At approximately 17 d before calving, cows were enrolled in the study; this time frame allowed for a minimum 3-d training period in addition to 2 wk of baseline data collection before calving. During this time, cows were housed in a close-up pen and trained to eat out of individual automated feed bins (Insentec B.V., Marknesse, the Netherlands). Each cow was assigned her own bin, and trained to eat only out of that bin during the 3-d period. At approximately 2 wk before calving ($d -13.4 \pm 4.9$), cows had an average BW of 847.7 ± 77.6 kg and an average BCS of 3.7 ± 0.34 . The close-up pen had 12 automated feed bins, 24 freestalls, and 2 water troughs. There were never more than 12 cows in the close-up pen at one time, ensuring

that each cow had access to her own individual feed bin. Cows spent 3.1 ± 3.2 d in the maternity pen before calving and 5.2 ± 3.3 d in the maternity pen after calving. The maternity pens were individual boxstalls (3.5×4.9 m) with individual access to feed and water. After calving, cows were milked in their maternity pens using a portable milking system.

Dry cows were fed a dry cow TMR (Tables 1 and 2) $1 \times/d$ between 1000 and 1100 h. The total amount of feed offered was adjusted daily to target approximately 10% refusals per bin (actual = $14.7 \pm 12.3\%$). The dry cow feed bins were cleaned out each day at approximately 0930 h every morning. After calving and following exit from the maternity pens, cows were moved to a lactating pen and again assigned to an individual feed bin. The lactating cow pen had 15 automated feed bins, 30 freestalls, and 2 water troughs. There were never more than 15 cows in the lactating pen at one time, ensuring that each cow had access to her own individual feed bin. Lactating cows were fed $1 \times/d$ between 1300 and 1400 h. The total amount of feed offered was adjusted daily to target approximately 10% refusals per bin (actual = $13.0 \pm 15.6\%$). Lactating cows were milked $2 \times/d$ at 0500 and 1700 h in a milking parlor.

The use of cows and experimental procedures complied with the guidelines of the Canadian Council on Animal Care (2009) and were approved by the University of Guelph Animal Care Committee (Animal Use Protocol #2518).

Experimental Design

Sample size and power analyses were used to calculate (as per Morris, 1999) the minimum number of replicates needed per treatment ($n = 20$) to detect a 10% level of observed mean difference for the primary outcome variables, including DMI, rumination, sorting, and milk production. Estimates of variation for these variables were based on previously reported values (DeVries et al., 2007; DeVries and Gill, 2012). Due to the likelihood of technical complications associated with the monitoring equipment used in our study, more than 20 cows per treatment were initially enrolled in the study to ensure the target sample size was achieved.

Upon calving, cows were randomly assigned to 1 of 2 dietary treatments (Table 1, 2), a TMR that differed in the length of the wheat straw component in that diet (Table 2), specifically (1) straw chopped with a 2.54-cm screen (short; $n = 21$) or (2) straw chopped with a 5.08-cm screen (long; $n = 20$). For both treatments, straw was chopped using a bale processor (Haybuster Model H-1150, Jamestown, ND). Cows were fed these treatment diets from 1 to 28 DIM. Treatment allocation was reviewed throughout the study to ensure it was

Table 1. Ingredient and chemical composition (mean $\pm$ SD) of the dry cow and experimental TMR

Composition	Dry diet	Lactation diet	
		Long straw ¹	Short straw ²
Ingredient (% DM)			
Corn silage ³	42	34	34
Wheat straw ⁴	21	9 ⁵	9 ⁶
Alfalfa haylage ⁵	16	26	26
High-moisture corn	—	19	19
Dry cow supplement ⁶	21	—	—
Lactating cow supplement ⁷	—	12	12
Chemical composition ⁸			
DM (%)	48.3 $\pm$ 2.9	49.0 $\pm$ 3.9	49.0 $\pm$ 4.8
OM (% of DM)	92.2 $\pm$ 0.5	91.8 $\pm$ 0.8	92.1 $\pm$ 0.8
CP (% of DM)	13.6 $\pm$ 1.0	15.9 $\pm$ 2.0	15.5 $\pm$ 1.8
ADF (% of DM)	30.5 $\pm$ 1.3	22.4 $\pm$ 1.9	22.7 $\pm$ 1.7
NDF (% of DM)	44.1 $\pm$ 1.8	32.6 $\pm$ 2.7	33.0 $\pm$ 2.5
Starch (% of DM)	17.0 $\pm$ 1.2	26.1 $\pm$ 2.0	26.4 $\pm$ 2.4
NFC (% of DM)	34.6 $\pm$ 1.8	43.3 $\pm$ 2.3	43.5 $\pm$ 3.0
Ca (% of DM)	1.0 $\pm$ 0.1	1.1 $\pm$ 0.2	1.1 $\pm$ 0.1
P (% of DM)	0.4 $\pm$ 0.0	0.5 $\pm$ 0.1	0.5 $\pm$ 0.1
NE _L (Mcal/kg of DM)	1.52 $\pm$ 0.02	1.63 $\pm$ 0.03	1.63 $\pm$ 0.03

¹Straw in long lactating diet was chopped using a 5.08-cm screen.

²Straw in short lactating diet was chopped using a 2.54-cm screen.

³Corn silage had a DM of 41.1 $\pm$ 8.0% and chemical composition (DM basis) of 7.3 $\pm$ 0.6% CP, 18.6 $\pm$ 1.5% ADF, 30.6 $\pm$ 1.8% NDF, and 40.8 $\pm$ 0.7% starch.

⁴Straw had a DM of 90.0 $\pm$ 2.9% and chemical composition (DM basis) of 4.8 $\pm$ 0.7% CP, 55.6 $\pm$ 1.1% ADF, and 77.4 $\pm$ 1.1% NDF.

⁵Alfalfa (80%) and timothy grass (20%) haylage had a DM of 39.7 $\pm$ 6.3% and chemical composition (DM basis) of 17.6 $\pm$ 1.5% CP, 35.3 $\pm$ 0.5% ADF, and 41.4 $\pm$ 2.3% NDF.

⁶Manufactured and supplied by Floradale Feed Mill Ltd. (Floradale, Ontario, Canada) including ingredients (% of DM) 38.2% Soy Plus, 20.2% soy hulls (ground), 19.1% canola, 15.3% wheat shorts, 9.6% soybean meal, 2.2% Diamond V Yeast XP, 2.1% limestone calcium carbonate, 1.5% magnesium oxide, 1.1% vitamin E, 1.1% fine salt, 1.1% tallow, 0.6% FFM Org Ruminant Micro PRX, 0.08% Alkosel 2000, 0.06% Rumensin, and 0.01% Rovimix Biotin 20,000.

⁷Manufactured and supplied by Floradale Feed Mill Ltd. including ingredients (% of DM) 49.1% Soy Plus, 35.9% soybean meal, 4.6% limestone calcium carbonate, 4.3% sodium sesquicarbonate, 4.0% fine salt, 3.9% fish meal (herring), 3.0% monocalcium phosphate, 2.2% magnesium oxide, 2.0% Diamond V Yeast XP, 1.0% FFM Org Ruminant Micro P, 0.4% Metasmart, 0.06% Rumensin, and 0.03% Selpex 2000.

⁸Values were obtained from chemical analysis of TMR samples. OM = 100 – % ash. NFC = 100 – (% CP + % NDF + % fat + % ash). NE_L was calculated based on NRC (2001) equations.

balanced for parity and milk production in the previous lactation (10,334.4 $\pm$ 1,955.7 kg). Each day, the basal diet, without straw, was prepared using a TMR mixer (Jaylor Model 5572, Jaylor Fabricating, Orton, ON, Canada). Feed was then transferred to a feed cart (Super Data Ranger; American Calan, Northwood, NH) and the appropriate amount of straw was added and mixed before delivery. Cows remained on their respective treatments for 4 wk postcalving. The lactating cow TMR was formulated to attempt, at minimum, to meet the nutrient requirements of early-lactation dairy cows producing 36 kg/d (NRC, 2001).

Behavioral Data Collection

Feeding behavior and DMI were monitored using the automated feed bins, as validated by Chapinal et al. (2007). From the recorded data, the duration of each

visit to the feed bin, the amount of feed consumed (start weight – end weight) during each visit, and the rate of consumption for each visit were calculated. These data were then summarized to calculate daily DMI (kg/d), daily time spent feeding (min/d), and average feeding rate (kg/min). Individual feeding bouts were combined and separated into meals using a meal criterion (i.e., the minimum duration of time between meals) calculated for each cow. Meal criteria for both the dry period and lactating period were calculated for each cow using methods described by DeVries et al. (2003); a software package (MIX 3.1.3; MacDonald and Green, 1988) was used to fit normal distributions to the frequency of log₁₀-transformed intervals of time between feeding visits. Meal frequency (no./d) was determined for each cow by summarizing the number of intervals between feeding events that exceeded their meal criterion. Meal length (min/meal) was calculated as the time between

the start of the first feeding visit, until the end of the last visit within the meal criterion. Meal size (kg of DM/meal) was calculated as DMI divided by meal frequency.

An electronic monitoring system (HR-TAG-LD, SCR Engineers Ltd., Netanya, Israel) was used to monitor rumination activity, as validated by Schirmann et al. (2009). Rumination data loggers, attached to a nylon neck collar, were fitted to each cow 2 wk before their expected calving date. Until the cow gave birth, and then for the first 4 wk of lactation, rumination activity was monitored 24 h/d. The system contained a radio frequency reader, which allowed data from the collars to be continuously uploaded to the control unit. These data, stored in 2-h intervals, were used to determine total time spent ruminating throughout each day.

Health Data Collection

At the time of enrollment, cow BW was recorded (I-20W scale, Ohaus, Dundas, ON, Canada) and BCS was recorded using a 5-point scale, as described by

Table 2. Particle size distribution¹ (% DM) of the straw, the experimental lactating cow diets (including straw), and the chemical composition of the particle fractions of those diets (mean ± SD)

Item	Lactation diet	
	Long straw ²	Short straw ³
Straw (% of DM)		
19-mm sieve	14.1 ± 6.9	1.4 ± 0.8
8-mm sieve	39.8 ± 4.7	25.0 ± 4.8
4-mm sieve	17.4 ± 1.0	24.8 ± 1.7
<4-mm pan	28.6 ± 10.5	48.9 ± 3.4
TMR (% of DM; including straw)		
19-mm sieve	6.4 ± 4.2	4.2 ± 3.6
8-mm sieve	38.9 ± 5.7	39.4 ± 6.2
4-mm sieve	19.3 ± 2.3	20.5 ± 3.4
<4-mm pan	35.4 ± 7.0	36.0 ± 7.0
ADF ⁴ (% of screen DM)		
19-mm sieve	31.5 ± 1.0	28.9 ± 1.2
8-mm sieve	26.6 ± 0.9	25.8 ± 1.0
4-mm sieve	18.6 ± 0.5	19.5 ± 1.0
<4-mm pan	13.9 ± 0.5	15.2 ± 1.2
NDF ⁴ (% of screen DM)		
19-mm sieve	45.2 ± 1.2	40.7 ± 1.9
8-mm sieve	37.7 ± 1.6	36.6 ± 2.0
4-mm sieve	28.2 ± 1.0	29.4 ± 1.8
<4-mm pan	21.2 ± 1.0	23.7 ± 1.7

¹Particle size determined by Penn State particle separator (Nasco, Fort Atkinson, WI), which has a 19-mm screen (long), 8-mm screen (medium), 4-mm screen (short), and a pan (fine).

²Straw in the long lactating diet was chopped using a 5.08-cm screen.

³Straw in the short lactating diet was chopped using a 2.54-cm screen.

⁴Values were obtained from chemical analysis of separated TMR samples.

Wildman et al. (1982). Assessment of BW and BCS occurred once during the dry period at enrollment and every 14 d starting on d 4 postcalving for a total of 3 measurements, including a final weighing on the last day of the trial period. To ensure accuracy for BCS, interobserver reliability testing was conducted between 3 individuals, with a resultant 85% accuracy rate. One of these individuals conducted the BCS for the entirety of the trial.

Wireless telemetry boluses (eBolus, eCow Ltd., Devon, UK) were used to measure reticulorumen pH to assess rumen health (as validated by Falk et al., 2016). At time of enrollment, the boluses were administered orally using a balling gun. Data consisted of reticulo-rumen pH data points at 15-min intervals for 24 h/d throughout the trial period. Data were downloaded 3 d/wk during the dry period and every 3 d postcalving. Data were amalgamated into a continuous record for each individual cow. Time spent below a pH threshold of 5.8 was then calculated along with daily mean, minimum, and maximum pH values. An absolute value for area below pH 5.8 was calculated by subtracting the pH value from 5.8 and multiplying it by the time spent at that pH value. These values were summed by day, creating a single value for area under the curve (AUC) for each day for each cow. These values were also standardized for intake by dividing by DMI for each day for each cow (Penner et al., 2009).

Blood BHB was assessed weekly before calving starting on the day of enrolment and every 4 d postcalving starting on d 4 after calving. For blood sampling, cows were restrained in a stall to obtain a small blood sample (~0.5 mL) from the coccygeal vein. Blood BHB was measured using an electronic hand-held device (Free-Style Precision Neo, Abbott Diabetes Care, Saint Laurent, QC, Canada), as validated by Kanz et al. (2015). Blood BHB concentrations >1.2 mmol/L were deemed indicative of subclinical ketosis (SCK; Geishauser et al., 1998; McArt et al., 2012). Testing of BHB occurred just before feed delivery (0930 h for dry cows and 1230 h for lactating cows) throughout the study.

Milk Yield and Components

Milk yield was recorded at every milking in the milking parlor (using DelPro software, DeLaval, Peterborough, ON, Canada) for the 4 wk cows were observed on treatment. Milk samples were collected from each cow, at each milking, on 2 consecutive days each week starting at d 6. These samples were sent to a DHI testing laboratory (CanWest DHI, Guelph, ON, Canada) for component analysis (fat, CP, MUN, and SCC) using a Fourier Transform Infrared full-spectrum analyzer

(Milkoscan FT+ and Milkoscan 6000; Foss, Hillerød, Denmark). One compositional value per cow on each sampling day was obtained by calculating the average across milkings.

Milk composition samples were used to determine the yield of 4% FCM (kg/d), calculated as $[0.4 \times \text{milk yield (kg/d)}] + [15.0 \times \text{fat yield (kg/d)}]$ (NRC, 2001). Energy-corrected milk was calculated as ECM (kg/d) = $(0.327 \times \text{kg of milk}) + (12.95 \times \text{kg of fat}) + (7.2 \times \text{kg of protein})$ (Tyrrell and Reid, 1965). Efficiency of milk production was calculated as kilograms of milk, 4% FCM yield, and ECM yield per kilogram of DMI per cow.

Feed Sampling and Analysis

Throughout the study, 2 fresh feed samples were collected 3×/wk; 1 sample was collected to determine DM and chemical composition and the other sample was collected to determine particle size distribution. Samples of the TMR components were also collected once monthly to be analyzed for DM and chemical composition. During the dry period, Orts samples were collected 3×/week to determine particle distribution for calculation of sorting. Orts samples were collected every 3 d during the lactating period starting on d 4 for the same purpose. All samples were immediately frozen at -20°C until further analysis.

After a 12-h period of thawing, fresh and Orts TMR samples collected for particle size analysis were processed using a 4-screen Penn State particle separator (PSPS; Maulfair et al., 2011; Jones and Heinrichs, 2013), which separates the sample into 4 fractions based on particle size as long (>19 mm), medium (<19 , >8 mm), short (<8 , >4 mm), and fine (<4 mm). Separated samples were then oven-dried at 55°C for 48 h.

The sorting of each PSPS fraction was calculated (as per Leonardi and Armentano, 2003) by dividing the actual amount of feed consumed of each fraction by the predicted amount of feed consumed of that fraction and expressing it as a percentage. For each fraction, the actual amount consumed was calculated by subtracting the DM refused from the DM offered, as determined by the PSPS analysis. The predicted amount consumed for each fraction was calculated as the product of the DMI of the total diet multiplied by the DM percentage of that fraction in the fed TMR. If the sorting value equaled 100%, then no sorting of the particle fraction occurred, a value $<100\%$ indicated sorting against that particle size fraction, whereas a value $>100\%$ indicated sorting in favor of that particle fraction.

Feed samples collected for nutrient composition analysis included the fresh TMR samples, feed components, and fresh TMR PSPS fractions. These samples were

oven-dried at 55°C for 48 h and then were ground to pass through a 1-mm screen (Model 4 Wiley Laboratory Mill, Thomas Scientific, Swedesboro, NJ). Ground samples, pooled by week, were then sent to Cumberland Valley Analytical Services Inc. (Maugansville, MD) for analysis of DM (135°C ; AOAC International, 2000: method 930.15), ash (535°C ; AOAC International, 2000: method 942.05), ADF (AOAC International, 2000: method 973.18), NDF with heat-stable α -amylase and sodium sulfite (Van Soest et al., 1991), CP ($\text{N} \times 6.25$; AOAC International, 2000: method 990.03; Leco FP-528 Nitrogen Analyzer, Leco, St. Joseph, MI), and starch (Hall, 2009).

Statistical Analyses

All statistical analyses were conducted using SAS 9.4 software (SAS Institute Inc., Cary, NC). The experimental design used was a completely randomized design. Due to technical failures of 3 reticulorumen pH boluses, all analyses involving reticulorumen pH were conducted using a sample size of 38 cows (long, $n = 19$; short, $n = 19$). Remaining analyses were conducted using a sample size of 41 cows (long, $n = 20$; short, $n = 21$). Significance was declared at $P \leq 0.05$ and tendencies were reported if $0.05 < P \leq 0.10$. If the P -value of an interaction term was ≤ 0.05 it was considered, otherwise interaction terms were disregarded. Prior to analyses, data were assessed for normality using the UNIVARIATE procedure of SAS; all assumptions of normality were met for all data. Residuals were compared with determine homogeneity of variance.

To investigate the effect of dietary treatment on feed sorting, feeding behavior, DMI, rumination behavior, reticulorumen pH, and milk production and composition, data were summarized by week of lactation (1 to 4) and analyzed using the MIXED procedure of SAS, treating week as a repeated measure. The model included the fixed effects of week, treatment, and the week $\times$ treatment interaction. The subject of the repeated statement was cow. Compound symmetry was selected as the covariance structure on the basis of best fit according to Schwarz's Bayesian information criterion. The PDIF procedure was used in the LS MEANS statement for analyzing differences between the week $\times$ treatment interactions when differences were detected. Covariate measures from the dry period were used for detecting differences between treatments for DMI and feeding behavior. To determine the occurrence of sorting within treatments, the summarized data for each particle size were tested for a difference from 100 using t -tests (Leonardi and Armentano, 2003; DeVries et al., 2007). Differences in sorting were analyzed using the previously described MIXED procedure model.

Given the known effect of precalving BCS on risk of elevated BHB postcalving (Gillund et al., 2001), cows were categorized as having a normal dry period BCS if their dry period BCS (collected at enrolment) was ≤ 3.5 (long: $n = 8$, short: $n = 6$) or as having a high dry period BCS if their dry period BCS was > 3.5 (long: $n = 12$, short: $n = 15$). To test the effect of treatment on blood BHB concentration, data were analyzed using the MIXED procedure of SAS, treating day of blood sampling as a repeated measure. The model included the fixed effects of day of blood sampling, treatment, dry period BCS category, and the dry period BCS category $\times$ treatment interaction. The subject of the repeated statement was cow. Compound symmetry was selected as the covariance structure based on best fit according to Schwarz's Bayesian information criterion.

In addition to determining the mean response to treatment, we also sought to understand how the response variables evolved, within treatment, over the course of the trial period. Thus, to model the changes over the 28-d postcalving period in DMI, rumination time, milk yield, mean reticulorumen pH, and time spent below a reticulorumen pH, an analysis of covariance was conducted to determine any significant linear, quadratic, or cubic effects of day (as per Schwaiger et al., 2013; DeVries et al., 2014). To accomplish this, data were analyzed using the MIXED procedure of SAS. The fixed effects of treatment, day, treatment $\times$ day, day², treatment $\times$ day², day³, and treatment $\times$ day³ were tested with the random effect of cow. Starting with the highest order term, those terms that were nonsignificant ($P > 0.05$) were removed from the model in a stepwise manner until only significant ($P \leq 0.05$) terms remained in the model. When an interaction was significant, the lower order term was removed.

RESULTS

Cows sorted the longest ration particles (> 19 mm) differently by treatment (Table 3); cows on the long treatment sorted against the longest particles ($P < 0.001$), whereas cows on the short treatment did not sort for or against those particles ($P = 0.88$). Cows on the long treatment did not sort for or against the medium particles ($< 19, > 8$ mm; $P = 0.97$), whereas cows on the short treatment sorted in favor of those particles ($P = 0.03$); however, a difference between treatments in sorting of the medium fraction was not detected (Table 3). Cows on the long treatment did not sort for or against the short particles ($< 8, > 4$ mm; $P = 0.19$), whereas cows on the short treatment selected in favor of those particles ($P = 0.02$); however, we detected no difference in sorting for the short particles between treatments (Table 3). Cows tended to sort the fine fraction (< 4

mm) differently by treatment (Table 3); cows on the long treatment did not sort for or against the fine fraction ($P = 0.86$), whereas cows on the short treatment sorted against this fraction ($P = 0.009$).

We found no differences between treatments detected in DMI or feeding behavior during the 4-wk study period (Table 4). The only exception was a treatment $\times$ week interaction ($P = 0.02$) for within-meal interval length (min). In the first week postcalving, cows on the long treatment tended to spend more time not eating within a meal than cows on the short treatment (5.7 ± 0.8 vs. 3.6 ± 0.8 min; $P = 0.06$); we observed no differences in within-meal interval length between treatments for wk 2 to 4 postcalving ($P = 1.0$). Cumulative DMI over the first 28 DIM was similar between treatments (long: 494.3 ± 16.6 kg; short: 499.6 ± 16.2 kg; $P = 0.82$). No effect of treatment was detected on time spent ruminating per day during the study period (Table 4).

We noted no differences detected between treatments for mean, minimum, or maximum daily reticulorumen pH during the 4-wk study period (Table 5). We also found no difference between treatments in daily time spent below a reticulorumen pH of 5.8 or AUC for a reticulorumen pH of 5.8 (Table 5). Daily milk production, composition, component yield, and milk efficiency were not affected by treatment (Table 6). However, the cumulative milk yield for the 4-wk study period tended to be different between treatments ($P = 0.07$); cows on the short treatment tended to produce more milk ($1,013.0 \pm 28.1$ kg) than cows on the long treatment (937.8 ± 28.8 kg).

Eighteen cows on the long treatment ($n = 20$) and 20 cows on the short treatment ($n = 21$) had at least 1 blood BHB concentration reading of ≥ 1.2 mmol/L

Table 3. Effect of straw particle size on the sorting (%)¹ of lactating dairy cows in the first 28 d of lactation (mean $\pm$ SE)²

Sorting of particle fractions ³ (%)	Treatment ⁴		P-value
	Long	Short	
Long	94.2 $\pm$ 1.9*	99.7 $\pm$ 1.9	0.049
Medium	100.0 $\pm$ 0.8	101.8 $\pm$ 0.8*	0.12
Short	100.7 $\pm$ 0.5	101.3 $\pm$ 0.5*	0.44
Fine	99.8 $\pm$ 1.2	96.8 $\pm$ 1.2*	0.08

¹Sorting = DMI refused/DMI predicted for each fraction. Sorting % = 100 means no sorting occurred, < 100 means sorting occurred against, and > 100 means sorting occurred in favor.

²Long, $n = 20$ cows; short, $n = 21$ cows.

³Particle size determined by Penn State particle separator (Nasco, Fort Atkinson, WI), which has a 19-mm screen (long), 8-mm screen (medium), 4-mm screen (short), and a pan (fine).

⁴Long: TMR with long (chopped with 5.08-cm screen) wheat straw particles; Short: TMR with short (chopped with 2.54-cm screen) wheat straw particles.

*Difference in sorting values from 100% ($P < 0.05$). All other values are $P > 0.05$.

Table 4. Effect of straw particle size on the DMI and feeding behavior of lactating dairy cows¹ in the first 28 d of lactation (mean $\pm$ SE)

Item	Treatment ²		P-value
	Long	Short	
DMI (kg/d)	19.0 $\pm$ 0.5	19.0 $\pm$ 0.5	0.98
DMI as a percentage of BW (%)	2.6 $\pm$ 0.08	2.6 $\pm$ 0.08	0.86
Feeding time (min/d)	163.0 $\pm$ 8.7	163.3 $\pm$ 8.5	0.98
Feeding rate (kg of DM/min)	0.14 $\pm$ 0.006	0.14 $\pm$ 0.006	0.90
Meal frequency (meals/d)	9.5 $\pm$ 0.5	9.2 $\pm$ 0.5	0.66
Within meal intervals (min)	4.5 $\pm$ 0.6	4.1 $\pm$ 0.6	0.65
Meal length (min/meal)	23.4 $\pm$ 1.6	23.1 $\pm$ 1.5	0.89
Meal size (DMI/meal)	2.2 $\pm$ 0.1	2.3 $\pm$ 0.1	0.50
Intervals between meals (min)	142.8 $\pm$ 8.4	148.1 $\pm$ 8.0	0.65
Meal criterion (min)	18.2 $\pm$ 2.8	18.0 $\pm$ 2.7	0.97
Rumination time (min/d)	474.1 $\pm$ 17.7	478.1 $\pm$ 17.3	0.87

¹Long: n = 20 cows; short: n = 21 cows.²Long: TMR with long (straw chopped using a 5.08-cm screen) wheat straw particles; short: TMR with short (straw chopped using a 2.54-cm screen) wheat straw particles.

during the study period. No differences were detected between treatments for mean BHB concentration (long: 1.6 $\pm$ 0.15 mmol/L; short: 1.5 $\pm$ 0.15 mmol/L; P = 0.66), days to first diagnosis of SCK (long: 8.3 $\pm$ 1.2 d; short: 8.1 $\pm$ 1.2 d; P = 0.87), and number of SCK diagnoses (long: 4.9 $\pm$ 0.6; short: 4.3 $\pm$ 0.5; P = 0.46). We also detected no differences between treatments for cows classified as either a normal or high dry period BCS (P = 0.30).

Changes in DMI, reticulorumen pH, time spent below a reticulorumen pH of 5.8, rumination time, and milk production over the 28-d study period were modeled. The fitted data indicated treatment differences between linear coefficients (P < 0.001) for daily DMI (Figure 1). The fitted data for mean daily reticulorumen pH indicated treatment differences between linear coefficients (P < 0.001; Figure 2). Treatment differences were noted between the linear coefficients (P < 0.001), quadratic coefficients (P < 0.001), and cubic coefficients

(P < 0.001) for fitted data for mean daily time spent below a reticulorumen pH of 5.8 (Figure 3). We found treatment differences detected between y -intercepts (P = 0.05), quadratic coefficients (P < 0.001), and cubic coefficients (P < 0.001) for daily rumination time (Figure 4). The fitted data indicated treatment differences between the linear coefficients (P < 0.001), quadratic coefficients (P < 0.001), and cubic coefficients (P < 0.001) for daily milk yield (Figure 5).

DISCUSSION

Particle size of the wheat straw included at 9% of DM to a fresh cow diet had an effect on the feed sorting behavior of early-lactation cows in this study. The short diet did not prevent feed sorting as hypothesized. Instead, cows on the short diet sorted their feed to a small degree in favor of the medium and short particles and sorted against the fine particles. Sorting in favor

Table 5. Effect of straw particle size on the reticulorumen pH of lactating dairy cows in the first 28 d of lactation (mean $\pm$ SE)¹

Item	Treatment ²		P-value
	Long	Short	
Mean reticulorumen pH	6.2 $\pm$ 0.05	6.2 $\pm$ 0.05	0.63
Maximum reticulorumen pH	6.6 $\pm$ 0.05	6.6 $\pm$ 0.05	0.50
Minimum reticulorumen pH	5.9 $\pm$ 0.05	5.9 $\pm$ 0.05	0.60
Mean time below reticulorumen pH 5.8 (min/d)	140.9 $\pm$ 47.8	97.6 $\pm$ 48.1	0.53
AUC ³ pH < 5.8 (pH $\times$ min/d)	19.9 $\pm$ 9.0	15.2 $\pm$ 9.1	0.72
AUC/DMI ⁴	1.0 $\pm$ 0.5	1.1 $\pm$ 0.5	0.96

¹Long, n = 19 cows; short, n = 19 cows.²Long: TMR with long (straw chopped using a 5.08-cm screen) wheat straw particles; short: TMR with short (straw chopped using a 2.54-cm screen) wheat straw particles.³AUC = area under curve.⁴AUC/DMI = area under curve pH < 5.8 (pH $\times$ min/d) divided by DMI (kg/d).

Table 6. Effect of straw particle size on the milk production and composition of lactating dairy cows in the first 28 d of lactation (mean ± SE)^{1,2}

Item	Treatment ³		<i>P</i> -value
	Long	Short	
Milk production (kg/d)			
Milk	36.4 ± 1.1	38.1 ± 1.1	0.31
4% FCM	44.4 ± 1.7	46.2 ± 1.6	0.45
ECM	48.5 ± 2.9	52.2 ± 3.0	0.38
Milk composition (%)			
Fat	5.1 ± 0.1	5.2 ± 0.1	0.79
Protein	4.1 ± 1.0	4.3 ± 0.94	0.90
Milk component yield (kg/d)			
Fat	1.9 ± 0.08	2.0 ± 0.1	0.56
Protein	1.5 ± 0.4	1.8 ± 0.4	0.62
Efficiency of milk production (kg/kg)			
Milk/DMI	2.0 ± 0.06	2.1 ± 0.06	0.49
4% FCM/DMI	2.3 ± 0.09	2.5 ± 0.08	0.27
ECM/DMI	2.5 ± 0.2	2.8 ± 0.2	0.27
MUN (mg/dL)	10.4 ± 0.5	10.0 ± 0.4	0.62
Log SCC ⁴	4.7 ± 0.2	4.7 ± 0.3	0.98

¹Long, n = 20 cows; short, n = 21 cows.
²Milk composition and efficiency data were averaged over 2 d/wk.
³Long: TMR with long (straw chopped using a 5.08-cm screen) wheat straw particles; short: TMR with short (straw chopped using a 2.54-cm screen) wheat straw particles.
⁴Somatic cell counts (cells/mL) were log-transformed, given that they did not meet the assumption of normality.

of some of the longer dietary particles and against the finest particles is unusual because cows typically sort in the opposite direction, favoring the shorter particles and avoiding the longer particles (Miller-Cushon and DeVries, 2017). Comparatively, cows fed the diet with longer straw particles sorted against the longest ration

particles. Greater sorting against these long particles on that diet was hypothesized, as researchers have revealed that cows demonstrate more sorting against long particles when particle size is more easily distinguished (Oelker et al., 2009; DeVries and Gill, 2012). We also noted greater NDF content in the longest particle

Figure 1. Daily DMI (kg/d) for cows fed 1 of 2 dietary treatments differing in the length of the wheat straw component: (1) straw chopped using a 2.54-cm screen (short: n = 21 cows) or (2) straw chopped using a 5.08-cm screen (long: n = 20 cows). Trend lines were constructed using analysis of covariance: $y = 1.42d - 0.080d^2 + 0.0015d^3 + 11.44$ for the long treatment; $y = 1.46d - 0.080d^2 + 0.0015d^3 + 11.15$ for the short treatment.

Figure 2. Mean daily reticulorumen pH for cows fed 1 of 2 dietary treatments differing in the length of the wheat straw component: (1) straw chopped using a 2.54-cm screen (short, n = 19 cows) or (2) straw chopped using a 5.08-cm screen (long, n = 19 cows). Trend lines were constructed using analysis of covariance: $y = -0.083d + 0.0060d^2 - 0.00012d^3 + 6.51$ for the long treatment; $y = -0.080d + 0.0060d^2 - 0.00012d^3 + 6.43$ for the short treatment.

Figure 3. Mean time (min/d) spent below a reticulorumen pH of 5.8 for cows fed 1 of 2 dietary treatments differing in the length of the wheat straw component: (1) straw chopped using a 2.54-cm screen (short; $n = 21$ cows) or (2) straw chopped using a 5.08-cm screen (long; $n = 20$ cows). Trend lines were constructed using analysis of covariance: $y = 61.11d - 4.53d^2 + 0.091d^3 - 33.73$ for the long treatment; $y = 16.13d - 1.50d^2 + 0.032d^3 + 93.88$ for the short treatment.

fraction of the long ration compared with that in the short ration, which was expected given the differences in particle size of the straw in both diets. As cows will sort against NDF (DeVries et al., 2007), this greater proportion of NDF further explains why cows on the long treatment sorted against the longest particle fraction to a greater extent.

Figure 4. Mean rumination time (min/d) postcalving for cows fed 1 of 2 dietary treatments differing in the length of the wheat straw component: (1) straw chopped using a 2.54-cm screen (short; $n = 21$ cows) or (2) straw chopped using a 5.08-cm screen (long; $n = 20$ cows). Trend lines were constructed using analysis of covariance: $y = 47.85d - 3.12d^2 + 0.061d^3 + 278.43$ for the long treatment; $y = 47.85d - 2.67d^2 + 0.047d^3 + 229.93$ for the short treatment.

Figure 5. Mean daily milk yield for cows fed 1 of 2 dietary treatments differing in the length of the wheat straw component: (1) straw chopped using a 2.54-cm straw screen (short; $n = 21$ cows) or (2) straw chopped using a 5.08-cm screen (long; $n = 20$ cows). Trend lines were constructed using analysis of covariance: $y = 4.081d - 0.24d^2 + 0.0044d^3 + 17.44$ for the long treatment; $y = 3.13d - 0.18d^2 + 0.0032d^3 + 22.34$ for the short treatment.

We found no detectable differences between treatments for mean pH, maximum pH, and minimum pH, summarized on a weekly basis. When day-to-day changes were analyzed over time, cows on the long treatment experienced a greater linear decrease in reticulorumen pH during the first 7 to 10 DIM than cows on the short treatment. Sorting against the long particles by cows on the long treatment may have contributed to a less stable reticulorumen environment. DeVries et al. (2008) demonstrated that sorting against long particles was associated with depressed rumen pH. Similarly, despite no treatment differences in mean time (min/d) spent below a reticulorumen pH of 5.8, the regression analysis revealed differences in how time spent below a reticulorumen pH of 5.8 varied by treatment across the first 28 DIM. During the first 10 DIM, cows on the long treatment exhibited a greater linear increase in time spent below a reticulorumen pH of 5.8 than cows on the short treatment. Between 10 and 23 DIM the opposite effect was observed, with long cows experiencing a greater decrease in time spent below a reticulorumen pH of 5.8. Cows on the long diet sorted against the longest, and most physically effective components, of the feed; this may have altered the buffering capacity of the reticulorumen (Zebeli et al., 2012) and thus contributed to greater fluctuations in reticulorumen pH. The fluctuation over time in reticulorumen pH observed in cows on the long treatment was unexpected given that the pH of fluid in the reticulum, where the bolus was mostly situated, fluctuates to a lesser degree than ruminal fluid

pH (Falk et al., 2016). Falk et al. (2016) suggested that the reason reticular pH is more stable is because the reticulum is smaller than the rumen and the contents are less varied; a smaller reticular volume likely minimizes movement of the bolus; this stabilization may provide more consistent measurements. Additionally reticulum contents have a higher pH than those of the rumen (Sato et al., 2012). Sato et al. (2012) suggested that a reticular pH of 6.3 or less was indicative of SARA, but did not provide a minimum time requirement for this threshold. It is possible that more pronounced differences between treatments in measures of pH in the current study may have been observed if measurement of pH were taken within the ventral rumen sac.

Despite a lack of a detectable difference in weekly mean DMI between treatment groups, when expressed as a change over time, cows on the short diet had a greater linear daily increase in DMI over the duration of the trial than cows on the long diet. A plateau in DMI was observed for both treatment groups between approximately 10 and 20 DIM, which is unusual for fresh cows, who typically experience a rapid increase in DMI in early lactation (Kertz et al., 1991). To ensure that any differences between the 2 treatment diets were discernible, the straw content of the diets was higher than what allowed for maximal DMI in cows averaging 122 ± 62 DIM (9 vs 5% DM; Eastridge et al., 2017). Thus, it is possible that the DMI of cows on both trial diets were limited at around 10 DIM because of the high straw content. It is well established that wheat straw has lower NDF degradability, in comparison to many other forages (Spanghero et al., 2010); thus, its inclusion in a diet may increase the filling effect of said diet. Consequently, in the present study, the straw (at 9% DM inclusion) may have filled the rumen and limited intake, as was speculated in a recent study using a diet with 10% (DM) wheat straw (Eastridge et al., 2017). However, McCarthy et al. (2015c) suggested that DMI was limited by rumen fill when NDF intake reached 1.1% of BW in the first 3 wk of lactation for cows fed a diet with 11.5% DM wheat straw (McCarthy et al., 2015a,b). At no time in the present study did mean daily NDF intake, as a percentage of BW, reach 1.1%, suggesting that DMI was not limited only by the filling effect of the amount of straw in the diets.

An alternative explanation for the plateau in DMI is that it is related to the rapid decline in reticulorumen pH observed in the first 10 DIM. The beginning of the plateau in DMI immediately follows the peak in time spent below a reticulorumen pH of 5.8 at 7 to 10 DIM, when cows on the long treatment spent 267 min/d below this pH threshold. Whereas no definitive parameters exist for how long reticulorumen pH must be depressed to diagnose SARA, it is generally ac-

cepted that pH must be below 5.8 for several hours per day (Plaizier et al., 2008). With this threshold in mind, it seems plausible that cows on both treatments were experiencing SARA in the first 10 DIM, the symptoms of which include decreased DMI and milk production (Plaizier et al., 2008). In support of this theory, cows on the short treatment tended to produce 76 kg more milk over the first 28 DIM than cows on the long treatment, possibly due to consumption of a more consistent diet (relative to that predicted) and greater stability in their reticulorumen environment. These results are supported by Sova et al. (2013), who observed that group-level sorting against long particles was associated with decreased FCM yield, possibly as a result of a less stable reticulorumen environment.

Aside from time spent not eating within a meal, feeding behavior was unaffected by treatment. This was not expected, as changing forage particle size has been shown to affect time spent chewing for oat silage, corn silage, and alfalfa hay (Kononoff and Heinrichs, 2003; Leonardi et al., 2005b; Kahyani et al., 2013). However, Suarez-Mena et al. (2013) did not find a difference in time spent eating, chewing, or ruminating for nonlactating cows fed a diet differing in straw particle size, which is consistent with the findings of the current study. It may be that the difference between treatments in straw particle size, in both studies, was not large enough to elicit a response in chewing time. In the first week of lactation cows on the long treatment tended to spend more time not eating within a meal than cows on the short treatment. It is possible that the transition to a diet with a longer straw particle size initially required more chewing (Nasrollahi et al., 2016), which resulted in more time spent not actively consuming feed from the bin and greater within-meal intervals. After a period of adaptation, cows on the long treatment may have then been able to reduce the time spent not eating within a meal. However, these results are not supported by Yang and Beauchemin (2006a), who found that increasing the forage particle size of barley silage did not result in more chewing within a meal. The discrepancy between their study and the current study may be the result of differences in forage sources. It is possible that straw takes longer within a meal to chew than silage; support for this is provided by Sudweeks et al. (1981), who demonstrated that oat straw has a higher chewing time per kilogram of DM than other forage sources, such as hay and various silages.

Whereas we detected no treatment differences in weekly mean time spent ruminating, straw particle size did affect how time spent ruminating evolved over the first 28 DIM. Cows on the short treatment showed less fluctuation in rumination time after 10 DIM. Cows on the short treatment had a lower initial daily rumination

time after calving than cows on the long treatment but recovered faster in the first 10 DIM. These results are consistent with the stabilization of reticulorumen pH in cows on the short treatment, likely due to the difference in sorting behavior on that diet, as discussed above. Stimulating rumination by feeding forage is important for maintaining a stable reticulorumen environment because rumination results in increased rates of salivation, which then buffers the reticulorumen pH (Oba and Allen, 1999).

Milk yield evolved differently by treatment across the first 28 DIM. During the first 10 DIM, cows on long treatment exhibited a greater linear increase in milk yield. However, after this initial surge in milk yield, cows on both treatments experienced a plateau in daily milk yield, which slightly declined until 23 DIM. A high incidence rate of SCK across treatments, in addition to the plateau in DMI, may explain why a plateau in milk yield occurred for both treatment groups. Of the 41 cows used in this trial, 38 (long, $n = 18$; short, $n = 20$) were diagnosed with SCK at least once during the trial period. There is an association between decreased milk production and increased BHB concentrations post-calving (Ospina et al., 2010); thus, this higher than expected incidence rate of SCK may have contributed to the plateau in milk yield observed in our study (Ospina et al., 2010; McArt et al., 2012). It is also interesting to note that, based on the fitted data, cows on the long treatment experienced greater declines in milk yield compared with cows on the short treatment from 10 to 23 DIM. This difference is likely not the result of SCK, as we found no treatment differences in measures of BHB concentration. It is more plausible that greater fluctuations in reticulorumen pH and rumination during the same time period, created by sorting against the longest particles in the ration, resulted in more variable milk yield for cows on the long treatment over the first 28 DIM.

CONCLUSIONS

Over the first 28 DIM, cows sorted in favor of the medium and short particles and against the finest ration particles when fed a diet containing shorter chopped wheat straw. In contrast, cows sorted against the longest ration particles during that time period when the diet contained longer chopped wheat straw. These differences in sorting behavior explain why cows fed the diet with the shorter chopped straw demonstrated more stability in their rumination and reticulorumen pH over the first 28 d of lactation. Consequently, cows fed a diet with a shorter straw particle size exhibited more stability in their milk production and tended to produce more cumulative milk over that time period

than cows fed a diet with straw chopped to a longer particle size. These results highlight the importance of managing forage particle size in early-lactation diets to promote consistency in intake, relative to that predicted, and resultant stability in reticulorumen health and milk yield.

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