Comparison of prepartum low-energy or high-energy diets with a 2-diet far-off and close-up strategy for multiparous and primiparous cows

B. F. Richards,¹ N. A. Janovick,¹ K. M. Moyes,¹ D. E. Beever,^{2*} and J. K. Drackley^{1†}

¹Department of Animal Sciences, University of Illinois, Urbana 61801

²Keenan Systems, Borris, County Carlow, Ireland R95 AY27

ABSTRACT

Previous research demonstrated that nutrition during the far-off (early) dry period may be as important to transition success as nutrition during the close-up dry period. Our objectives were to determine if a low-energy, high-fiber diet fed throughout the dry period improved metabolic status and production of dairy cows compared with a higher-energy diet or a 2-diet system, and to compare responses of cows and heifers to those diets. Holstein cows ($n = 25$ with 10 primiparous per treatment) were assigned to each of 3 diets at 60 d before expected calving. Treatment LO [40.5% wheat straw; 5.6 MJ of net energy for lactation (NE_L)/kg of DM] was designed to meet but not exceed National Research Council recommendations for ad libitum intake from dry-off until calving. Treatment HI was a high-energy diet (6.7 MJ of NE_L /kg of DM) fed for ad libitum intake from dry-off until calving. For the LO+HI treatment, the LO diet was fed ad libitum from dry-off until 21 d before expected calving, followed by the HI diet until parturition. After parturition all cows were fed a lactation diet (7.0 MJ of NE_L /kg of DM) through 63 d postpartum. Dry matter intake and body weight were greater for HI cows prepartum, but not postpartum. When LO+HI cows were switched to the HI diet, their dry matter intake increased to match that of HI cows. Cows fed HI had greater gain of body condition before calving but lost more postpartum. Energy balance postpartum was higher for LO cows than for HI cows. Milk production, protein content, and protein yield did not differ among diets. Milk fat content and yield were highest for HI cows, lowest for LO, and intermediate for LO+HI cows. The HI cows had lower serum nonesterified fatty acids prepartum than either LO or LO+HI, but greater concentrations postpartum.

Serum β -hydroxybutyrate did not differ prepartum, but was greater for HI than for LO or LO+HI postpartum. Serum glucose and insulin were lower for LO than HI and LO+HI prepartum; insulin was lower for LO and HI than for LO+HI postpartum. The LO cows had lower liver total lipid concentration postpartum than the HI cows and LO+HI cows. Primiparous cows generally responded to diets the same as multiparous cows. The LO+HI feeding strategy provided no benefit over the LO diet. Moreover, the high-energy diet, even when fed for only 19 d before calving in the LO+HI group, resulted in increased serum β -hydroxybutyrate and liver total lipid concentrations compared with LO. **Key words:** dry period, transition, production, metabolism

INTRODUCTION

Controlled feeding of cows during the dry period affects periparturient health, postcalving DMI, and lactation performance (Beever, 2006; Janovick et al., 2011). Dann et al. (2006) found that nutrition during the far-off dry period was more important than nutrition during the close-up dry period for transition success; DMI and energy balance increased, and serum BHB and nonesterified fatty acids (**NEFA**) decreased when diets were fed to meet NRC (2001) guidelines during the early dry period (far-off period) compared with overfeeding.

Janovick and Drackley (2010) found that a high-straw diet (32% wheat straw; 9.08 MJ of ME/kg of DM and 142 g of CP/kg of DM) fed during the entire dry period resulted in DMI being maintained more constant to calving, less lipid accumulation in the liver, and lower blood ketone bodies than cows fed a higher-energy diet for ad libitum intake (11.21 MJ of ME/kg of DM and 150 g of CP/kg of DM). These effects were similar to when prepartum DMI was limited by feed restriction (Dann et al., 2006; Douglas et al., 2006; Janovick and Drackley, 2010). Restricting the amount of feed offered to cows is difficult in group housing systems. Aggressive cows will have ad libitum intake, whereas more timid

Received March 27, 2020.

Accepted June 2, 2020.

*Deceased.

†Corresponding author: drackley@illinois.edu

cows may have severely restricted intake. Including straw or other bulky forage in a TMR provides a way for feeding for ad libitum DMI while still controlling energy intake (Beever, 2006; Dann et al., 2006).

Many farmers continue to use a “steam-up” or close-up diet of greater nutrient density before calving based on recommendations from nutritionists. Surprisingly little research evidence exists, however, to support this practice (Drackley and Dann, 2008; Mann et al., 2015). Whether a close-up diet would provide benefits to cows fed on high-bulk diets during the early dry period also is not clear (Dann et al., 2006). Single-diet, single group dry cow programs have merit for small- to medium-size farms that have difficulties creating multiple pens of cows. Moreover, many farms commingle first-calving heifers with older cows in such management schemes, but little research is available to assess the nutritional outcomes of this practice. Heifers may respond differently or in different magnitude to nutritional manipulations compared with older cows (Vandehaar et al., 1999).

The objectives of our study were to (1) compare metabolic status and productivity of cows fed a controlled-energy, high-fiber diet throughout the entire dry period with cows fed a 2-diet dry cow system (controlled-energy far-off diet and higher-energy close-up diet), and (2) compare responses of second lactation and older cows with those of first-calving heifers. A negative control group also was included in which cows and heifers were fed the higher-energy close-up diet throughout the entire dry period. Our hypothesis was that the 1-diet group with energy intake controlled to near requirements would have less lipid mobilization and greater milk production than the 2-diet group, and that performance and health for both would exceed that of the 1-diet overfed group.

MATERIALS AND METHODS

Cows, Dietary Treatments, and Management

Thirty-one first-calving heifers and 48 second or greater lactation Holstein cows were randomly assigned on the basis of expected calving date to 1 of 3 prepartum dietary strategies. Cows were dried off at approximately 60 d before expected calving and were started on the experimental diets immediately after dry-off. Some cows were already dry because of long calving intervals and were started on diets at approximately 60 d prepartum; the number of these cows was balanced across all diets. First-parity heifers were moved to the experimental barn at the same time and were housed and fed together with the older cows for 60 d before expected calving.

Diet composition is presented in Table 1 and nutrient composition in Table 2. The first dietary treatment was a controlled-energy, high-fiber diet (1 diet, low energy; **LO**) designed to meet, but not exceed, NRC (2001) requirements [formulated to 5.6 MJ (1.35 Mcal) of NE_L/kg of DM and 11.9% CP, DM basis] when fed for ad libitum intake from dry-off until calving. This diet included wheat straw (40.5% of the DM) chopped directly into the TMR in a horizontal paddle mixer with knives (Keenan Klassik 140 mixer wagon, Keenan Systems, Borris, Ireland). Cows on the second treatment (1 diet, high energy; **HI**) were fed a high-energy diet [formulated to 6.7 MJ (1.61 Mcal) of NE_L/kg of DM and 12.8% CP, DM basis; Tables 1 and 2] for ad libitum intake from dry-off until calving. The third treatment (2 diets; **LO+HI**) represented a typical 2-phase system in which the LO diet was fed for ad libitum intake from dry-off until 21 d prepartum, followed by feeding the HI diet until calving. We used a “partial DCAD” approach for all cows and heifers in which magnesium chloride and magnesium sulfate were added but we did not attempt to reach a negative dietary cation-anion difference (DCAD). At parturition all cows were fed a common lactation diet [formulated to 7.0 MJ (1.67 Mcal) of NE_L/kg of DM and 17.5% CP; Tables 1 and 2]. A small amount (approximately 2 kg) of long-stem alfalfa hay was offered to all cows as a top-dress to the lactation TMR for 10 d following parturition. Measurements were made through 63 d postpartum.

Multiparous cows assigned to each dietary group averaged 2.5, 3.0, and 3.1 parities for LO, HI, and LO+HI, respectively, with the mode being 2 parities for each group. Previous 305-d mature equivalent milk production did not differ among treatments and averaged 12,748, 13,150, and 13,693 kg for LO, HI, and LO+HI, respectively. The average pretreatment BCS was 3.1, 3.2, and 3.1 for the 3 groups.

Cows were housed prepartum in a freestall barn equipped with Calan gates (American Calan, Northwood, NH) allowing for daily measurements of individual feed intake (feed offered minus feed refused, including top-dressed hay). Cows were moved into box stalls adjacent to the freestall pens when parturition was imminent. Cows were housed postpartum in a tie-stall barn, bedded on chopped straw over rubber mats, and fed in concrete mangers.

Calving difficulty was scored on a scale of 1 to 5, where a score of 1 was assigned when a cow calved between observations without showing signs of parturition, a score of 2 was assigned when a cow showed signs of parturition and calved without assistance in <6 h from first observation, a score of 3 was assigned when a cow was observed for 6 h and the calving progressed naturally without assistance, a score of 4 was assigned

Table 1. Ingredient composition of diets (% of total DM)

Ingredient	Low ¹	High ¹	Lactation
Wheat straw	40.46	0.00	0.00
Alfalfa hay, mid-maturity	3.24	6.00	3.50
Alfalfa silage, mid-maturity	9.70	17.92	12.50
Corn silage	28.32	49.88	34.00
Whole cottonseed	0.00	4.99	9.00
Ground-shelled corn	3.46	13.83	21.50
Soybean meal 48%	11.33	4.29	2.50
SoyPlus ²	0.00	0.00	8.50
Soy hulls	0.00	0.00	5.00
Blood meal	0.00	0.00	1.00
Liquid fat	0.00	0.00	0.25
Urea	0.24	0.19	0.00
Dicalcium phosphate	0.32	0.00	0.20
Limestone	0.65	0.62	0.55
Magnesium oxide	0.51	0.43	0.15
Magnesium sulfate	0.69	0.62	0.00
Magnesium chloride	0.40	0.55	0.00
Sodium sulfate	0.00	0.00	0.10
Sodium bicarbonate	0.00	0.00	0.75
Mineral and vitamin premix ³	0.19	0.18	0.20
Salt (plain)	0.20	0.23	0.20
Vitamin A ⁴	0.01	0.01	0.00
Vitamin D ⁵	0.01	0.01	0.00
Vitamin E ⁶	0.26	0.24	0.10

¹Low = 1 diet, low energy; high = 1 diet, high energy.

²Landus Cooperative, Ralston, IA.

³Contained 5% Mg, 10% S, 7.5% K, 2.0% Fe, 3.0% Zn, 3.0% Mn, 5,000 mg/kg of Cu, 250 mg/kg of I, 40 mg/kg of Co, 150 mg/kg of Se, 2,200 kIU/kg of vitamin A, 660 kIU/kg of vitamin D₃, and 7,700 IU/kg of vitamin E.

⁴Contained 30,000 kIU/kg.

⁵Contained 5,009 kIU/kg.

⁶Contained 44,000 IU/kg.

when the calving lasted >6 h and the cow required intervention without the use of mechanical assistance for calving, and a score of 5 was when the cow required intervention with the use of mechanical extraction because of the position or size of the calf. The first milking of colostrum was measured and recorded. Colostral IgG was estimated using a colostrometer.

DMI and Feed Analyses

Daily DMI was measured from assignment to diets (approximately 60 d prepartum) through 63 d postpartum. Dry matter content of individual feed ingredients was determined weekly and rations were adjusted accordingly to maintain DM ratios of ingredients in the TMR. Weekly samples of ingredients and TMR were frozen at -20°C and then composited monthly for analysis of DM, CP, NDF, ADF, starch, Ca, P, K, Cl, and Mg by standard wet chemistry techniques at a commercial laboratory (Dairy One, Ithaca, NY; Table 2). Estimated NE_L values were assigned by Dairy One using NRC (2001) assumptions and equations. Particle

Table 2. Analyzed composition of diets¹

Component	Diet ²		
	Low	High	Lactation
DM, % of fresh weight	52.4	48.4	56.2
CP, % of DM	12.0	14.4	16.9
NDF, % of DM	53.9	37.2	35.1
ADF, % of DM	37.5	25.4	23.5
NFC, ³ % of DM	24.6	41.9	40.4
Starch, ⁴ % of DM	12.4	27.2	25.1
NE _L , ³ MJ/kg of DM	5.61	6.74	6.99
ME, ³ MJ/kg of DM	9.04	10.62	11.00
Ca, % of DM	0.64	0.67	0.72
P, % of DM	0.25	0.31	0.40
Mg, % of DM	0.46	0.55	0.30
K, % of DM	1.57	1.41	1.37
Na, % of DM	0.08	0.11	0.32
Cl, ³ % of DM	0.62	0.56	0.32
S, % of DM	0.25	0.22	0.21
DCAD, ⁵ mEq/100 g	10.6	11.4	35.9
TMR particle size ⁶			
Top	20 ± 8	4 ± 2	7 ± 3
Middle	36 ± 4	46 ± 6	41 ± 3
Bottom	45 ± 7	50 ± 7	52 ± 4

¹Mean analyses of 9 monthly composite samples of TMR.

²Low = 1 diet, low energy; high = 1 diet, high energy.

³Calculated using NRC (2001) model.

⁴Analysis of one composite sample of individual ingredients.

⁵Dietary cation-anion difference calculated as (Na + K) - (Cl + S).

⁶Mean (±SD) particle size determined on each screen of the Penn State Particle Separator, expressed as the percentage of total weight on each screen.

size distribution was determined weekly for each of the TMR samples using a Penn State Particle Separator with 2 screens (19 and 8 mm) and a pan (Table 2).

Milk Production and Composition

Cows were milked twice daily and milk yields were recorded. Consecutive evening and morning milk samples were taken weekly starting at ≥6 through 63 DIM. Pooled milk samples were prepared in proportion to milk yield at each milking, preserved (800 Broad Spectrum Microtabs II; D & F Control Systems Inc., San Ramon, CA), and analyzed for contents of fat, protein, lactose, SNF, urea N, and SCC using mid-infrared techniques (Dairy Lab Services, Dubuque, IA).

Energy Balance, BW, and BCS

Pre- and postpartum energy balance was calculated using equations from the NRC (2001). Intake of NE_L was determined using daily DMI multiplied by NE_L density in the diet. Maintenance NE_L was calculated as $BW^{0.75} \times 0.080$. Pregnancy requirements for NE_L were calculated as $[(0.00318 \times \text{day of gestation} - 0.0352) \times$

(calf birth weight/45)]/0.218. Requirements of NE_L for milk production were calculated as $(0.0929 \times \text{fat, \%}) + (0.0547 \times \text{protein, \%}) + (0.0395 \times \text{lactose, \%})$. For primiparous cows, an additional 2.69 Mcal/d was added for retained energy for growth (i.e., NE_G) required during pregnancy as calculated previously for primiparous cows at the University of Illinois Dairy Research Unit (Janovick and Drackley, 2010).

Body weight was measured weekly for each cow at the same time after the morning milking and before feeding. A BCS (scale 1 = thin to 5 = obese, with quarter-point increments) was assigned to each cow weekly by 3 people independently and the median score was used for statistical analysis.

Blood and Liver Sampling and Analyses

Blood samples were obtained from the coccygeal vein or artery at 0600 h prepartum and 0700 h postpartum (after feed refusals were removed and before the morning feeding) weekly from 60 to 20 d before expected calving, twice weekly from 20 to 10 d before expected calving, 3 times weekly from 10 d before expected calving to 10 d postpartum, twice weekly from 10 to 20 d postpartum, and weekly from 20 to 63 d postpartum. Blood was collected into evacuated serum separator tubes containing clot activator (Becton Dickinson Vacutainer Systems, Franklin Lakes, NJ). Serum tubes were allowed to remain at ambient temperature for 30 min before separation. All tubes were centrifuged at $1,300 \times g$ for 15 min at room temperature to obtain serum, which then was divided into several aliquots that were stored at -20°C until analysis.

Insulin in serum was measured using a radioimmunoassay kit (Coat-a-Count Insulin kit, Diagnostic Products Corporation, Los Angeles, CA) as modified by Studer et al. (1993). Concentrations of albumin (Doumas et al., 1971; Albumin Plus kit, Roche Diagnostics Corp., Indianapolis, IN), glucose (Peterson and Young, 1968; glucose/HK kit, Roche Diagnostics Corp.), NEFA (Johnson and Peters, 1993), and BHB (Williamson and Mellanby, 1974; BHB kit number 310-A, Sigma Chemical Co., St. Louis, MO) were measured in serum using an autoanalyzer (University of Illinois Clinical Pathology Laboratory, Urbana, IL). For determination of albumin, glucose, NEFA, and BHB concentrations, all available time points corresponding to planned sample days were used. Only blood samples taken at d -14 , 1, 3, 5, 9, 30, and 60 were analyzed for insulin. These time points corresponded approximately with liver biopsy days, parturition, and completion of the experiment.

Liver was sampled via puncture biopsy (Hughes, 1962) from cows under local anesthesia at 0700 h on

d -14 , 10, and 30 relative to parturition. Liver tissue was frozen immediately in liquid N and later analyzed for concentrations of total lipid (Hara and Radin, 1978) and triacylglycerol (Fletcher, 1968; Foster and Dunn, 1973).

Health

The incidence of health problems was recorded and summarized. All cows clinically diagnosed with ketosis were verified by serum BHB concentrations greater than 1.4 mM. Other nonclinical cases of ketosis are reported based on serum BHB concentrations greater than 1.4 mM.

Statistical Analyses

Weekly means of daily measurements for DMI and milk yield were calculated for statistical analysis. To avoid problems with fitting covariance structure, pre- and postpartum data were analyzed separately, with far-off and close-up prepartum data also analyzed separately. Data were analyzed as a randomized design using the MIXED procedure of SAS (Hatcher and Stepanski, 1994) with the following model:

$$y_{ijkl} = \mu + W_i + P_j + WP_{ij} + D_k + WD_{ik} + PD_{jk} + WPD_{ijk} + C_{(ijk)l},$$

where y_{ijkl} = an observation from the i th time relative to calving, j th parity, k th diet, and l th cow; μ = the grand mean; W_i = effect of the i th week or day; P_j = effect of the j th parity; WP_{ij} = effect of the time by parity interaction; D_k = effect of the k th diet; WD_{ik} = effect of the time by diet interaction; PD_{jk} = effect of the parity by diet interaction; WPD_{ijk} = effect of the time by parity by diet interaction; and $C_{(ijk)l}$ = random experimental error from the l th cow nested within the i th time, j th parity, and k th diet. The REPEATED statement was used for variables measured over time (BW, BCS, DMI, milk yield, milk components, blood components, and liver composition). Degrees of freedom were estimated by using the Satterthwaite option in the model statement. Significance was declared when $P < 0.05$ and tendencies or trends were declared at $0.05 < P \leq 0.10$. When the diet effect was significant, least squares means were separated using the PDIFF option.

RESULTS

Median days dry for multiparous cows was 60, 58, and 61 for LO, HI, and LO+HI groups, with ranges of

36 to 170 d, 45 to 114 d, and 55 to 155 d, respectively. The mean $\pm$ standard deviation days on experimental diets before calving was 56 ± 7 , 56 ± 10 , and 57 ± 8 d for LO, HI, and LO+HI, respectively. Cows and heifers in the LO+HI group received the LO diet for 36 ± 7 d and the HI diet for a mean of 19 ± 6 d (mean $\pm$ SD).

A total of 10 cows originally assigned to diets were removed from the experiment before calving (4 multiparous and 3 primiparous cows not pregnant, aborted, or calved too early) or their data were removed from the prepartum data set (3 multiparous cows, did not adapt to Calan feed gates). Seven of these cows were replaced. The total number of cows in the final prepartum data set, therefore, was 23 for LO (13 cows and 10 heifers), 26 for HI (15 cows and 11 heifers), and 26 for LO+HI (16 cows and 10 heifers). Four cows (3 multiparous and 1 primiparous) were removed at or after calving due to death or trauma, but prepartum data for these cows were retained in the data set. A total of 3 multiparous cows had partial data postpartum that were included in the data set, before these cows died or were removed as downer cows. The total number of cows in the final postpartum data set was 23 for LO (13 cows and 10 heifers), 24 for HI (14 cows and 10 heifers), and 24 for LO+HI (14 cows and 10 heifers).

Intakes, Energy Balance, BW, and BCS

During the far-off period, DMI expressed both as kilograms per day and percentage of BW ($P < 0.01$), as well as intakes of CP and NE_M ($P < 0.01$), were greater for HI cows than for LO or LO+HI cows (Table 3). Mean intakes were similar for LO and LO+HI. The DMI for HI cows was high during the middle of the far-off dry period but then began to decrease (diet $\times$ week, $P < 0.01$; Figure 1), whereas DMI for LO and LO+HI was more constant. Heifers and cows generally responded similarly to diets (Table 3). The parity by diet interaction was not significant ($P = 0.33$) for DMI as a percentage of BW (Table 3). Diet by parity interactions were significant for DMI, CP intake, NE_M intake, and energy balance as a percentage of requirement, which occurred because the differences between LO and HI diets were greater for multiparous cows than for primiparous cows (data not shown). Differences in intake resulted in similar patterns among diets for energy balance, expressed either as megajoules per day or percentage of requirements (Table 3, Figure 2A). During the far-off period, HI cows consumed 51% more energy than their requirement, whereas LO and LO+HI cows consumed 3.8% and 12.1% less than their requirements ($P < 0.01$; Table 3, Figure 2A).

During the far-off period, the greater DMI and NE_M intake for HI cows resulted in the HI cows having greater mean BCS ($P < 0.01$) than either LO or LO+HI cows (Table 3). Mean BCS was not affected by interactions of parity with week or diet. Mean BW did not differ significantly among diets, but the tendency ($P = 0.06$) for a diet by week interaction is illustrated in Figure 2B. The parity by diet interaction was not significant.

The DMI decreased during the close-up period, with differences among diets narrowing (diet $\times$ week, $P < 0.08$; Figure 1). When LO+HI cows were switched to the same diet as the HI cows at 3 wk before expected calving, their DMI increased to the same as HI cows and then followed them down at the same rate until calving (Figures 1 and 2). Intakes of CP and NE_M followed the same pattern as DMI.

Energy balance was greater for cows fed HI and LO+HI than for those fed LO during the close-up period (Table 3). Cows fed HI consumed on average 14.6% more energy than requirements during the week before parturition while LO+HI cows consumed 10.9% more than requirements; LO cows consumed 12.2% less than requirements. Parity by diet interactions for energy balance were not significant. As in the far-off period, BCS was greater for HI, with LO and LO+HI not different from each other ($P < 0.01$). Mean BW did not differ among diets (Table 3).

Postpartum DMI did not differ ($P = 0.65$) among diets (Table 3). In contrast to what was observed prepartum, the HI cows had the most negative energy balance and LO cows the least negative; cows fed LO+HI were intermediate ($P < 0.01$). Mean BCS followed the same trend ($P = 0.06$) among diets as energy balance, with HI cows losing BCS more rapidly than LO or LO+HI cows (diet by week, $P < 0.01$; Figure 2C). No differences among diets or interactions were observed for postpartum BW.

Calving Data

The number of cows that calved with twins for LO, HI, and LO+HI groups was 3, 1, and 4, respectively. Mean calf birth BW did not differ among diets, and no difference was observed among diets in calving difficulty score (Table 4). Colostral IgG concentration did not differ among diets, and limited measurements of colostrum volume also indicated no differences (Table 4).

Milk Yield and Composition

Milk yield was not different among diets (Table 5) and the diet by parity interaction was not significant (P

Table 3. Dry matter and nutrient intakes, BW, and BCS pre- and postpartum

Stage and variable	Dietary treatment (D) ¹			Parity (P)		P-value							
	Low	High	Low+high	SEM	1	≥2	SEM	Diet	Parity	P × D	Week (W)	P × W	D × W
Far-off dry period													
DMI, kg/d	9.9 ^b	14.4 ^a	9.7 ^b	0.45	9.7	12.9	0.40	<0.01	<0.01	0.01	<0.01	0.25	<0.01
DML, % of BW	1.43 ^b	2.01 ^a	1.36 ^b	0.07	1.55	1.65	0.062	<0.01	0.22	0.33	<0.01	0.42	<0.01
CP intake, kg/d	1.20 ^b	2.02 ^a	1.10 ^b	0.05	1.22	1.66	0.045	<0.01	<0.01	<0.01	<0.01	0.24	0.11
NE _M intake, MJ/d	59.8 ^b	95.8 ^a	55.2 ^b	2.5	59.4	81.2	2.2	<0.01	<0.01	<0.01	<0.01	0.23	0.10
Energy balance, MJ/d	-5.2 ^b	28.7 ^a	-10.2 ^b	2.7	-5.8	14.7	2.4	<0.01	<0.01	0.12	<0.01	<0.06	<0.04
Energy balance, % of requirement	92.6 ^b	149.2 ^a	83.7 ^b	4.5	91.3	125.7	3.9	<0.01	<0.01	0.04	<0.01	0.30	0.02
BCS	3.20 ^b	3.35 ^a	3.19 ^b	0.03	3.22	3.27	0.027	<0.01	0.21	0.23	<0.01	0.16	0.23
BW, kg	700	716	711	16	628	790	14	0.76	<0.01	0.32	<0.01	0.99	0.05
Close-up dry period													
DMI, kg/d	9.9 ^b	12.8 ^a	12.2 ^a	0.50	10.8	12.5	0.44	<0.01	<0.01	0.65	<0.01	<0.01	0.08
DML, % of BW	1.39 ^b	1.73 ^a	1.67 ^a	0.07	1.65	1.54	0.062	<0.01	0.18	0.95	<0.01	0.01	0.05
CP intake, kg/d	1.27 ^b	1.83 ^a	1.74 ^a	0.06	1.47	1.75	0.065	<0.01	<0.01	0.92	<0.01	<0.01	0.02
NE _M intake, MJ/d	63.2 ^b	87.0 ^a	82.8 ^a	2.9	70.7	84.5	2.5	<0.01	<0.01	0.94	<0.01	<0.01	0.03
Energy balance, MJ/d	-5.2 ^b	18.7 ^a	13.3 ^a	3.2	2.0	15.8	2.8	<0.01	<0.01	0.92	<0.01	<0.01	0.02
Energy balance, % of requirement	93.2 ^b	128.7 ^a	119.4 ^a	4.8	103.4	124.2	4.4	<0.01	<0.01	0.88	<0.01	<0.01	0.02
BCS	3.13 ^b	3.45 ^a	3.20 ^b	0.04	3.28	3.24	0.037	<0.01	0.50	0.88	0.01	0.44	0.54
BW, kg	722	750	738	15	657	816	13	0.39	<0.01	0.33	<0.01	<0.01	0.28
Postpartum													
DMI, kg/d	17.2	16.3	16.8	0.70	15.4	18.0	0.61	0.65	<0.01	0.96	<0.01	<0.01	0.42
DML, % of BW	2.89	2.70	2.74	0.10	2.78	2.77	0.090	0.40	0.97	0.81	<0.01	0.02	0.46
CP intake, kg/d	3.04	2.91	2.93	0.12	2.71	3.21	0.10	0.70	<0.01	0.87	<0.01	0.02	0.72
NE _L intake, MJ/d	124.3	118.8	119.7	5.0	110.4	131.0	4.2	0.70	<0.01	0.87	<0.01	0.02	0.72
Energy balance, MJ/d	-8.4 ^a	-29.3 ^c	-20.1 ^b	3.8	-17.9	-20.6	3.4	<0.01	0.54	0.99	<0.01	<0.01	0.98
Energy balance, % of requirement	94.0 ^a	80.0 ^c	86.5 ^b	2.5	87.0	86.6	2.2	<0.01	0.90	0.89	<0.01	0.03	0.95
BCS	2.81	2.97	2.81	0.05	3.02	2.70	0.049	0.06	<0.01	0.88	<0.01	<0.01	<0.01
BW, kg	609	617	608	7.0	603	619	5	0.59	0.15	0.21	<0.01	0.11	0.44

^{a-c}Means within a row with unlike superscripts differ ($P \leq 0.05$).¹Low = 1 diet, low energy; high = 1 diet, high energy; low+high = 2 diets, low during far-off dry period and high during close-up dry period.

= 0.60). In contrast, yield of FCM was greater for HI cows than for either LO or LO+HI groups ($P = 0.03$), which did not differ from each other (Table 5). The greater FCM yield was mainly driven by differences in milk fat content. Both milk fat content and yield were lower ($P < 0.01$) for LO cows than for HI cows, with LO+HI being intermediate (Table 5). Content ($P = 0.34$) and yield ($P = 0.43$) of true protein in milk were not different among diets (Table 5). Contents of lactose and SNF in milk were lower ($P = 0.02$) for LO than for HI and LO+HI groups (Table 5); however, yields of

Figure 1. Dry matter intake (kg/d, A, and percent of BW, B) for multiparous and primiparous cows fed a low-energy diet for the entire dry period (low, ■), a high-energy diet for the entire dry period (high, ●), or the low-energy diet during the far-off dry period and the high-energy diet during the close-up dry period (low+high, ▲). Panel A: average SEM = 0.54 (far-off) and 0.57 (close-up). Effects in the far-off model: diet ($P < 0.001$), week ($P < 0.001$), and diet $\times$ week ($P = 0.009$). Effects in the close-up model: diet ($P < 0.001$), week ($P < 0.001$), and diet $\times$ week ($P = 0.08$). Panel B: average SEM = 0.08 (far-off) and 0.08 (close-up). Effects in the far-off model: diet ($P < 0.001$), week ($P < 0.001$), and diet $\times$ week ($P = 0.004$). Effects in the close-up model: diet ($P = 0.002$), week ($P < 0.001$), and diet $\times$ week ($P = 0.05$).

Figure 2. Prepartum energy balance (percent of requirement, A), prepartum weekly mean BW (kg, B), and postpartum weekly mean BCS (1 to 5 scale, C) for multiparous and primiparous cows fed a low-energy diet for the entire dry period (low, ■), a high-energy diet for the entire dry period (high, ●), or the low-energy diet during the far-off dry period and the high-energy diet during the close-up dry period (low+high, ▲). Panel A: average SEM = 5.4 (far-off) and 5.6 (close-up). Effects in the far-off model: diet ($P < 0.001$), week ($P < 0.001$), and diet $\times$ week ($P = 0.02$). Effects in the close-up model: diet ($P < 0.001$), week ($P < 0.001$), and diet $\times$ week ($P = 0.02$). Panel B: average SEM = 16.4 (far-off) and 14.9 (close-up). Effects in the far-off model: diet ($P = 0.76$), week ($P < 0.001$), and diet $\times$ week ($P = 0.06$). Effects in the close-up model: diet ($P = 0.39$), week ($P < 0.001$), and diet $\times$ week ($P = 0.28$). Panel C: average SEM = 0.06. Effects in the model: diet ($P < 0.06$), week ($P < 0.001$), and diet $\times$ week ($P = 0.01$).

lactose and SNF were not different among diets (Table 5). The calculated efficiency (FCM/DMI) was lowest for LO and highest for HI, with the LO+HI group being intermediate ($P < 0.01$; Table 5).

Blood and Liver Components

During the far-off period, serum NEFA concentration was greater ($P < 0.01$) for LO and LO+HI cows than for HI cows (Table 6), reflecting their lower energy balance compared with HI cows. Concentrations of BHB did not differ ($P = 0.22$) among diets, but serum glucose followed an inverse pattern to NEFA with glucose highest for the HI cows ($P = 0.01$). Urea N in blood was greater ($P = 0.05$) prepartum for LO than for LO+HI or HI (Table 6). Neither albumin nor cholesterol differed among diets.

During the close-up period, serum NEFA decreased when cows assigned to the LO+HI group were switched to the HI diet, such that NEFA were greater ($P < 0.01$) for LO than for either LO+HI or HI (Table 6). This undoubtedly reflects the large increase in energy balance (Table 3) and the resultant greater ($P = 0.02$) insulin concentration for LO+HI and HI compared with LO (Table 6). Concentration of BHB did not differ among diets (Table 6). Glucose was greater ($P < 0.01$) for cows fed HI and LO+HI than for those fed LO. Urea N was greater ($P < 0.01$) for cows fed LO than for those fed HI or LO+HI. Serum albumin did not differ among diets ($P = 0.17$). Serum total cholesterol was greater ($P < 0.01$) for HI than for either LO or LO+HI.

After parturition, serum NEFA for HI cows went from being lower than LO prepartum to significantly higher than the other 2 diets postpartum (Table 6). In addition, a significant treatment by day interaction (Figure 3A) was observed, demonstrating that the con-

centration of NEFA was greater for HI during early postpartum and then decreased but remained greater than LO and LO + HI throughout the study period. Corresponding to these data, the LO cows had lower ($P < 0.01$) serum BHB (Table 6) postpartum than did HI cows. In addition, concentrations of BHB returned to baseline more quickly (diet by day, $P < 0.01$) for LO than did those for cows fed the LO+HI diet (Figure 3B). Serum BHB remained elevated in HI cows for the duration of the study (Figure 3B).

Serum glucose postpartum (Table 6) did not differ ($P = 0.54$) among diets. The insulin concentration was greater for the LO+HI cows than for either LO or HI cows, resulting in a lower glucose:insulin ratio for that group. Concentrations of urea N, albumin, and cholesterol did not differ among diets postpartum when all cows were receiving the same diet.

Liver total lipid (Table 6, Figure 4A) and triacylglycerol (Table 6, Figure 4B) concentrations were lower ($P < 0.01$) postpartum for LO cows than for HI cows. For the LO+HI cows, total lipids did not differ from the HI cows; triacylglycerols did not differ from the LO group. Interactions of parity and diet were not significant, indicating that both parity groups responded to diet in the same way.

Health

The incidence of disease and deaths in our experiment is recorded in Table 7. Dietary treatment trends cannot be considered conclusive because there were not enough cows to reach statistically valid conclusions. Three of the metritis cases, 1 on the HI and 2 on the LO+HI treatment, were in cows that had twins. One cow with a retained placenta on the LO+HI treatment had twins. All cows reported as having retained placentas were also reported as having metritis.

Table 4. Calving and colostrum data

Variable	Dietary treatment (D) ¹			Average SEM	P-value		
	Low	High	Low+high		Diet	Parity (P)	P × D
Calf birth weight, ² kg	42.2	40.1	40.9	1.4	0.57	<0.01	0.69
Calving difficulty ³	1.54	1.64	1.78	0.26	0.83	0.98	0.36
Colostrum IgG, g/L	80.7	85.5	78.6	7.5	0.79	0.19	0.54
First colostrum weight, ⁴ kg	4.8	6.0	5.9	1.2	0.81	0.02	0.51

¹Low = 1 diet, low energy; high = 1 diet, high energy; low+high = 2 diets, low during far-off dry period and high during close-up dry period.

²Model included sex ($P < 0.05$).

³Scored on a scale of 1 to 5, where 1 = a cow calved between observations without showing signs of parturition, 2 = a cow showed signs of parturition and calved without assistance in <6 h from first observation, 3 = a cow was observed for 6 h and the calving progressed naturally without assistance, 4 = a calving that lasted >6 h and the cow required intervention without the use of mechanical assistance for calving, and 5 = a cow required intervention with the use of mechanical extraction.

⁴Measured only in 3, 6, and 6 cows for low, high, and low+high, respectively.

Table 5. Milk yield and milk components

Variable	Dietary treatment (D) ¹			Parity (P)		P-value							
	Low	High	Low+high	SEM	1	≥2	SEM	Diet	Parity	P × D	Week (W)	P × W	D × W
Milk yield, kg/d	32.2	33.6	33.1	1.4	29.5	36.4	1.3	0.80	<0.01	0.60	<0.01	0.01	0.78
FCM, kg/d	33.5 ^b	39.1 ^a	35.2 ^b	1.4	32.5	39.4	1.3	0.03	<0.01	0.73	<0.01	0.62	0.35
Milk fat, %	3.20 ^c	3.87 ^a	3.43 ^b	0.110	3.53	3.44	0.095	<0.01	0.35	0.34	<0.01	0.53	0.57
Milk protein, %	2.63	2.70	2.74	0.053	2.70	2.66	0.045	0.34	0.24	0.51	<0.01	0.05	0.37
Milk lactose, %	4.79 ^b	4.91 ^a	4.93 ^a	0.038	4.90	4.81	0.037	0.02	<0.01	0.99	<0.01	0.19	0.79
Milk SNF, %	5.67 ^b	5.80 ^a	5.82 ^a	0.039	5.79	5.70	0.038	0.02	<0.01	0.99	<0.01	0.15	0.74
Milk fat, kg/d	1.12 ^c	1.41 ^a	1.21 ^b	0.059	1.13	1.36	0.052	<0.01	<0.01	0.59	0.30	0.82	0.49
Milk protein, kg/d	0.93	1.01	0.98	0.043	0.87	1.06	0.037	0.43	<0.01	0.91	<0.01	0.01	0.39
Milk lactose, kg/d	1.70	1.84	1.78	0.075	1.59	1.94	0.065	0.41	<0.01	0.58	<0.01	0.08	0.41
Milk SNF, kg/d	2.01	2.17	2.10	0.088	1.88	2.29	0.077	0.44	<0.01	0.59	<0.01	0.08	0.39
MUN, mg/dL	12.22	12.28	11.87	0.38	11.59	12.61	0.33	0.67	0.02	0.84	0.94	0.57	0.45
Milk SCC, ×1,000	252	170	155	85	89	296	74	0.69	0.04	0.63	0.63	0.78	0.92
Efficiency, FCM/DMI	1.91 ^c	2.34 ^b	2.09 ^a	0.08	2.08	2.15	0.071	<0.01	0.45	0.89	<0.01	0.22	0.52

^{a-c}Means within a row with unlike superscripts differ ($P \leq 0.05$).¹Low = 1 diet, low energy; high = 1 diet, high energy; low+high = 2 diets, low during far-off dry period and high during close-up dry period.

DISCUSSION

Our major findings from this study were that feeding a higher-energy close-up diet in a 2-diet system had little effect relative to a controlled-energy diet fed throughout the dry period, and that first-calving heifers responded similarly to older cows. Changes during the far-off dry period were as expected given the dietary differences in energy intake, and agree with previous experiments from our group (Dann et al., 2006; Douglas et al., 2006; Janovick and Drackley, 2010) and others (Agenäs et al., 2003; Huang et al., 2014; Mann et al., 2015). The LO+HI treatment failed to increase production, indicating that feeding a higher-energy diet before parturition did not increase milk production. We tested the possible consequences of the slightly greater number of lactations and greater previous milk yields for the LO+HI cows; however, these factors were not significant when used as covariates in a statistical model in which only multiparous cows were analyzed (data not shown). Feeding the LO+HI diet resulted in metabolic responses in blood and liver, including increased serum BHB and increased liver lipid that were intermediate to the LO and HI groups.

Although milk yield did not differ among diets, FCM and milk fat yield were greater for cows fed HI. The greater milk fat production for HI cows likely was attributable to the greater BCS loss after calving. While this would represent a short-term economic benefit, it must be weighed against the greater metabolic risks associated with increased body lipid mobilization.

Our results confirm previous data demonstrating that long-term overfeeding during the dry period increases likelihood of significant lipid deposition in the liver and greater ketogenesis postpartum (Rukkwamsuk et al., 1998; Dann et al., 2006; Janovick et al., 2011), and that controlled-energy diets prevent this hepatic lipid accumulation and ketogenesis (Janovick et al., 2011; Vickers et al., 2013; Huang et al., 2014; Mann et al., 2015). These results support the more negative energy balance, greater milk fat yield, and excessively high calculated efficiency in HI cows compared with the other groups. The generally greater incidence of health problems for HI cows is consistent with results of Janovick et al. (2011), as well as field results reported by Beever (2006) and Colman et al. (2011). Surprisingly, however, our data indicate that even the relatively short (19 d) period of feeding the HI diet before calving for LO+HI cows significantly increased hepatic lipid infiltration and BHB concentrations. Similar responses were observed by Ji et al. (2012) in a more limited number of cows.

The HI cows had significantly increased NEFA and BHB concentrations postpartum despite insulin con-

Table 6. Components in blood and liver pre- and postpartum

Stage and variable	Dietary treatment (D) ¹			Parity (P)			P-value							
	Low	High	Low+high	SEM	1	≥2	SEM	Diet	Parity	P × D	Day (T)	P × T	D × T	
Serum, far-off dry period														
NEFA, ² mEq/L	0.38 ^a	0.18 ^b	0.46 ^a	0.03	0.38	0.29	0.03	<0.01	0.01	0.39	0.76	<0.01	0.10	
BHB, mmol/L	0.39	0.39	0.45	0.029	0.40	0.41	0.025	0.22	0.80	0.42	<0.01	0.43	0.95	
Glucose, mg/dL	65.1 ^c	68.2 ^a	65.2 ^b	0.8	68.2	64.2	0.7	0.01	<0.01	0.59	<0.01	0.68	0.61	
Urea N, mg/dL	13.8 ^a	12.4 ^b	12.6 ^b	0.4	11.6	14.3	0.4	0.05	<0.01	0.70	<0.01	0.98	0.75	
Albumin, g/dL	3.64	3.68	3.66	0.067	3.56	3.76	0.058	0.92	<0.01	0.51	0.37	0.82	0.54	
Cholesterol, mg/dL	120.2	124.6	112.6	5.5	96.3	141.9	4.9	0.29	<0.01	0.39	<0.01	<0.01	0.60	
Serum, close-up dry period														
NEFA, mEq/L	0.53 ^a	0.34 ^b	0.35 ^b	0.03	0.41	0.40	0.03	<0.01	0.68	0.30	<0.01	<0.01	0.46	
BHB, mmol/L	0.55	0.46	0.48	0.03	0.47	0.52	0.03	0.14	0.22	0.89	<0.01	0.07	0.60	
Glucose, mg/dL	61.5 ^b	66.8 ^a	65.5 ^a	1.0	67.8	61.3	0.9	<0.01	<0.01	0.39	<0.01	<0.01	0.56	
Insulin, uIU/mL	8.4 ^b	12.4 ^a	14.8 ^a	1.5	14.7	9.1	1.4	0.02	<0.01	0.89	—	—	—	
Glucose:insulin, mg/uIU	0.12	0.08	0.07	0.02	0.10	0.21	0.02	0.13	0.01	0.62	—	—	—	
Urea N, mg/dL	13.8 ^a	11.1 ^b	10.0 ^b	0.4	11.0	12.3	0.4	<0.01	<0.01	0.31	<0.01	0.03	0.10	
Albumin, g/dL	3.44	3.63	3.53	0.070	3.40	3.62	0.064	0.17	0.05	0.73	0.42	0.59	0.79	
Cholesterol, mg/dL	84.0 ^b	98.8 ^a	82.9 ^b	3.2	84.4	92.8	2.8	<0.01	0.03	<0.01	<0.01	0.18	0.71	
Serum, postpartum														
NEFA, mEq/L	0.52 ^b	0.77 ^a	0.60 ^b	0.04	0.60	0.66	0.04	<0.01	0.17	0.58	<0.01	0.01	0.01	
BHB, mmol/L	0.53 ^b	0.81 ^a	0.64 ^b	0.065	0.63	0.70	0.057	0.01	0.42	0.75	<0.01	<0.01	<0.01	
Glucose, mg/dL	63.0	61.7	63.3	1.1	68.6	59.2	1.3	0.54	<0.01	0.14	<0.01	<0.01	0.41	
Insulin, ⁴ uIU/mL	8.6 ^b	7.3 ^b	12.2 ^a	0.8	13.0	5.7	0.77	<0.01	<0.01	0.11	<0.01	0.04	0.29	
Glucose:insulin, mg/uIU	0.16 ^a	0.18 ^a	0.10 ^b	0.02	0.08	0.21	0.02	0.05	<0.01	0.38	<0.01	0.04	0.72	
Urea N, mg/dL	12.6	12.2	12.0	0.4	11.4	13.1	0.4	0.58	<0.01	0.38	<0.01	0.07	0.26	
Albumin, g/dL	3.4	3.5	3.5	0.05	3.5	3.4	0.05	0.45	0.08	0.35	0.03	0.14	0.56	
Cholesterol, mg/dL	116.5	124.6	122.1	5.0	127.7	114.7	4.4	0.53	0.03	0.99	<0.01	0.02	0.53	
Liver														
Total lipid, % of wet weight	5.2 ^b	9.0 ^a	7.3 ^a	0.8	6.9	7.5	0.7	<0.01	0.51	0.37	<0.01	0.08	0.02	
Triacylglycerol, % of wet weight	1.1 ^b	3.5 ^a	1.9 ^b	0.4	1.5	2.8	0.4	<0.01	0.02	0.71	<0.01	<0.01	0.03	

^a Means within a row with unlike superscripts differ ($P \leq 0.05$).¹ Low = 1 diet, low energy; high = 1 diet, high energy; low+high = 2 diets, low during far-off dry period and high during close-up dry period.² Parity × dietary treatment × day interaction ($P = 0.02$). NEFA = nonesterified fatty acids.³ Parity × dietary treatment × day interaction ($P = 0.05$).⁴ Parity × dietary treatment × day interaction ($P = 0.09$).

Table 7. Incidence of disease, twins, and deaths

Parity	Dietary treatment ¹	Mastitis	Retained placenta	Metritis	LDA ²	Clinical ketosis	BHB >1.4 mM	Milk fever	Twins	Deaths
1	High	0	0	1	0	2	3	0	0	0
	Low	0	0	1	1	0	3	0	1	1
	Low+high	0	0	0	0	0	1	0	1	0
≥2	High	1	3	6	2	2	9	1	1	3
	Low	3	3	5	1	3	5	0	2	1
	Low+high	3	2	3	3	3	7	0	3	2
All	High	1	3	7	2	4	12	1	1	3
	Low	3	3	6	2	3	8	0	3	2
	Low+high	3	2	3	3	3	8	0	4	2

¹Low = 1 diet, low energy; high = 1 diet, high energy; low+high = 2 diets, low during far-off dry period and high during close-up dry period.

²LDA = left displaced abomasum.

Figure 3. Serum nonesterified fatty acid (NEFA) concentrations (mmol/L, A) and serum BHB concentrations (mmol/L, B) for multiparous and primiparous cows fed a low-energy diet for the entire dry period (low, ■), a high-energy diet for the entire dry period (high, ●), or the low-energy diet during the far-off dry period and the high-energy diet during the close-up dry period (low+high, ▲). Panel A: average SEM = 0.07. Effects in the model: diet ($P < 0.01$), week ($P < 0.001$), and diet $\times$ week ($P = 0.01$). Panel B: average SEM = 0.10. Effects in the model: diet ($P = 0.01$), week ($P < 0.001$), and diet $\times$ week ($P < 0.01$).

Figure 4. Total lipid concentrations (percent of wet tissue weight, A) and triacylglycerol (TAG) concentrations (percent of wet tissue weight, B) in liver tissue for multiparous and primiparous cows fed a low-energy diet for the entire dry period (low, ■), a high-energy diet for the entire dry period (high, ●), or the low-energy diet during the far-off dry period and the high-energy diet during the close-up dry period (low+high, ▲). Panel A: average SEM = 1.0. Effects in model: diet ($P = 0.004$), day ($P < 0.001$), and diet by day ($P = 0.02$). Panel B: average SEM = 0.6. Effects in model: diet ($P = 0.001$), day ($P < 0.001$), and diet by day ($P = 0.03$).

centrations and glucose:insulin ratios similar to the LO cows. In LO+HI cows, although nonsignificant, postpartal NEFA and BHB were intermediate to those of LO and HI cows, whereas insulin was significantly greater than either group. These results raise the possibility that overfeeding prepartum affects the ability of insulin to regulate lipolysis and lipid mobilization postpartum. Glucose tolerance tests have provided additional evidence for alterations in insulin activity (Holtenius et al., 2003; Schoenberg and Overton, 2011; Mann et al., 2016a). In contrast, Ji et al. (2012) and Mann et al. (2016c) presented evidence that insulin signaling in adipose tissue relative to glucose homeostasis was not altered by overfeeding. Indeed, Schoenberg et al. (2012) used a hyperinsulinemic, euglycemic clamp study to show that insulin action was not impaired in overfed dry cows. Ji et al. (2012) reported changes in mRNA abundance in adipose tissue that would indicate enhanced lipolysis and NEFA release during even a short period of overfeeding during the late dry period, which would be consistent with results of the present study. The explanation for the increased NEFA and BHB postpartum in overfed cows remains unclear (see discussion in Mann et al., 2016c), but may be related simply to lower DMI and energy balance early postpartum, which subsequently decreases insulin secretion and thereby allows greater NEFA mobilization (Mann et al., 2016c).

The rapid increase in DMI when LO+HI cows were switched to the HI diet resulted in those cows rising to DMI similar to the HI cows but then following them downward toward parturition. Similar results were observed by Mann et al. (2015). The initial DMI increase likely reflects responses to the lower dietary NDF of the HI diet and maintenance of rumen fill, whereas chemostatic or hormonal regulatory factors may have decreased intake as calving approached for both LO+HI and HI (Allen, 2000). The marked change in DMI and energy balance, with corresponding increases in insulin and decreased NEFA when the LO+HI cows were switched to the higher-energy diet were not maintained past the first week postpartum. However, although it appears that a 3-wk period of close-up feeding is not advantageous and might even be negative, the potential benefits of a short (7 to 10 d) "close-up" feeding period are intriguing and should be investigated in future research. We acknowledge that such a practice would be difficult to implement in group housing situations, unless cows were moved to maternity pens at 7 to 10 d before calving.

Concerns have been expressed about possible differences in calf birth BW and colostrum synthesis when lower energy diets are fed for extended times during

the dry period. The lack of difference in calf BW argues against any such effects. Likewise, previous studies from our group (Grum et al., 1996; Dann et al., 2006; Douglas et al., 2006; Janovick and Drackley, 2010) and others (Mann et al., 2015) have not shown differences in calf birth BW. However, numerical differences observed in some of those studies indicate that continued efforts to measure and aggregate effects of prepartal plane of nutrition on calf BW are warranted. Likewise, limited data in our study did not show any effects on colostrum volume or quality. In a similar study design, Mann et al. (2016b) also reported no significant effect on colostrum volume. Nevertheless, numerically lower mean values for first colostrum volume in cows fed LO in our study and that by Mann et al. (2016b) suggest that colostrum volume should be measured in future studies with the LO strategy in comparison with other dietary regimens.

A limitation of our study is that, other than making diets isonitrogenous, we did not attempt to equalize MP supplies among diets, in contrast to the design employed by Mann et al. (2015). Lower urea N during the far-off period for cows fed LO + HI than for LO is difficult to explain because LO and LO+HI were consuming the same diet. The lower urea N in blood of primiparous cows in our study might indicate that MP supply was marginal so that catabolism of AA was decreased due to the greater relative protein requirements for heifers. However, concentrations of albumin in blood were in normal ranges in both parity groups and did not differ among diets, which provides evidence that MP supplies were not limiting.

CONCLUSIONS

Our results confirm the generally favorable metabolic responses in cows fed LO throughout the dry period, compared with HI and LO+HI cows. These results indicate an increase in lipid accumulation in the liver and greater ketogenesis due to body reserve mobilization in HI cows, increasing the likelihood of fatty liver and subsequent disorders and diseases. Controlling the energy intake of cows during the dry period minimizes lipid accumulation and ketogenesis in the liver postpartum. The only major difference in cow performance due to the HI diet was the increased milk fat production (and thus yield of FCM). Although this would represent a temporary economic benefit, it must be balanced against a significant increase in DMI (and thus feed cost) over the duration of the dry period and greater risk of lipid-associated disorders postpartum. Compared with LO, the LO+HI treatment in this study did not appreciably benefit cows in any way except for

small increases in milk fat. Thus, the additional feed and inconvenience of formulating a separate diet for a separate group would not be justified by significant economic benefit. Indeed, the increased liver fat accumulation and prolonged elevation of BHB postpartum suggests that this approach might actually increase metabolic risk to cows postpartum.

ACKNOWLEDGMENTS

Funding for this experiment was provided by Richard Keenan and Sons (Borris, Ireland); Vita Plus (Madison, WI); and state and federal funds provided to the Illinois Agricultural Experiment Station (Urbana). The authors have not stated any conflicts of interest.

REFERENCES

- Agenäs, S., E. Burstedt, and K. Holtenius. 2003. Effects of feeding intensity during the dry period. 1. Feed intake, body weight, and milk production. *J. Dairy Sci.* 86:870–882. [https://doi.org/10.3168/jds.S0022-0302\(03\)73670-4](https://doi.org/10.3168/jds.S0022-0302(03)73670-4).
- Allen, M. S. 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. *J. Dairy Sci.* 83:1598–1624. [https://doi.org/10.3168/jds.S0022-0302\(00\)75030-2](https://doi.org/10.3168/jds.S0022-0302(00)75030-2).
- Beever, D. E. 2006. The impact of controlled nutrition during the dry period on dairy cow health, fertility and performance. *Anim. Reprod. Sci.* 96:212–226. <https://doi.org/10.1016/j.anireprosci.2006.08.002>.
- Colman, D. R., D. E. Beever, R. W. Jolly, and J. K. Drackley. 2011. Gaining from technology for improved dairy cow nutrition: Economic, environmental, and animal health benefits. *Prof. Anim. Sci.* 27:505–517. [https://doi.org/10.15232/S1080-7446\(15\)30532-5](https://doi.org/10.15232/S1080-7446(15)30532-5).
- Dann, H. M., N. B. Litherland, J. P. Underwood, M. Bionaz, A. D'Angelo, J. W. McFadden, and J. K. Drackley. 2006. Diets during far-off and close-up dry periods affect periparturient metabolism and lactation in multiparous cows. *J. Dairy Sci.* 89:3563–3577. [https://doi.org/10.3168/jds.S0022-0302\(06\)72396-7](https://doi.org/10.3168/jds.S0022-0302(06)72396-7).
- Douglas, G. N., T. R. Overton, H. G. Bateman II, H. M. Dann, and J. K. Drackley. 2006. Prepartal plane of nutrition, regardless of dietary energy source, affects periparturient metabolism and dry matter intake in Holstein cows. *J. Dairy Sci.* 89:2141–2157. [https://doi.org/10.3168/jds.S0022-0302\(06\)72285-8](https://doi.org/10.3168/jds.S0022-0302(06)72285-8).
- Doumas, B. T., W. A. Watson, and H. G. Biggs. 1971. Albumin standards and the measurement of serum albumin with bromocresol green. *Clin. Chim. Acta* 31:87–96. [https://doi.org/10.1016/0009-8981\(71\)90365-2](https://doi.org/10.1016/0009-8981(71)90365-2).
- Drackley, J. K., and H. M. Dann. 2008. A scientific approach to feeding dry cows. Chapter 3 in *Recent Advances in Animal Nutrition – 2007*. P. C. Garnsworthy and J. Wiseman, ed. Nottingham University Press, Nottingham, UK.
- Fletcher, M. J. 1968. A colorimetric method for estimating serum triglycerides. *Clin. Chim. Acta* 22:393–397. [https://doi.org/10.1016/0009-8981\(68\)90041-7](https://doi.org/10.1016/0009-8981(68)90041-7).
- Foster, L. B., and R. T. Dunn. 1973. Stable reagents for determination of serum triglycerides by a colorimetric Hantzsch condensation method. *Clin. Chem.* 19:338–340. <https://doi.org/10.1093/clinchem/19.3.338>.
- Grum, D. E., J. K. Drackley, R. S. Younker, D. W. LaCount, and J. J. Veenhuizen. 1996. Nutrition during the dry period and hepatic lipid metabolism of periparturient dairy cows. *J. Dairy Sci.* 79:1850–1864. [https://doi.org/10.3168/jds.S0022-0302\(96\)76553-0](https://doi.org/10.3168/jds.S0022-0302(96)76553-0).
- Hara, A., and N. S. Radin. 1978. Lipid extraction of tissue with a low-toxicity solvent. *Anal. Biochem.* 90:420–426. [https://doi.org/10.1016/0003-2697\(78\)90046-5](https://doi.org/10.1016/0003-2697(78)90046-5).
- Hatcher, L., and E. J. Stepanski. 1994. A Step-by-Step Approach to Using the SAS System for Univariate and Multivariate Statistics. SAS Institute Inc., Cary, NC.
- Holtenius, K., S. Agenas, C. Delavaud, and Y. Chilliard. 2003. Effects of feeding intensity during the dry period. 2. Metabolic and hormonal responses. *J. Dairy Sci.* 86:883–891. [https://doi.org/10.3168/jds.S0022-0302\(03\)73671-6](https://doi.org/10.3168/jds.S0022-0302(03)73671-6).
- Huang, W., Y. Tian, Y. Wang, A. Simayi, A. Yasheng, Z. Wu, S. Li, and Z. Cao. 2014. Effect of reduced energy density of close-up diets on dry matter intake, lactation performance and energy balance in multiparous Holstein cows. *J. Anim. Sci. Biotechnol.* 5:30–38. <https://doi.org/10.1186/2049-1891-5-30>.
- Hughes, J. P. 1962. A simplified instrument for obtaining liver biopsies in cattle. *Am. J. Vet. Res.* 23:1111–1113.
- Janovick, N. A., Y. R. Boisclair, and J. K. Drackley. 2011. Prepartum dietary energy intake affects metabolism and health during the periparturient period in primiparous and multiparous Holstein cows. *J. Dairy Sci.* 94:1385–1400. <https://doi.org/10.3168/jds.2010-3303>.
- Janovick, N. A., and J. K. Drackley. 2010. Prepartum dietary management of energy intake affects postpartum intake and lactation performance by primiparous and multiparous Holstein cows. *J. Dairy Sci.* 93:3086–3102. <https://doi.org/10.3168/jds.2009-2656>.
- Ji, P., J. S. Osorio, J. K. Drackley, and J. J. Looor. 2012. Overfeeding a moderate energy diet prepartum does not impair bovine subcutaneous adipose tissue insulin signal transduction and induces marked changes in periparturient gene network expression. *J. Dairy Sci.* 95:4333–4351. <https://doi.org/10.3168/jds.2011-5079>.
- Johnson, M. M., and J. P. Peters. 1993. Technical note: An improved method to quantify nonesterified fatty acids in bovine plasma. *J. Anim. Sci.* 71:753–756. <https://doi.org/10.2527/1993.713753x>.
- Mann, S., F. A. Leal Yepes, M. Duplessis, J. J. Wakshlag, T. R. Overton, B. P. Cummings, and D. V. Nydam. 2016a. Dry period plane of energy: Effects on glucose tolerance in transition dairy cows. *J. Dairy Sci.* 99:701–717. <https://doi.org/10.3168/jds.2015-9908>.
- Mann, S., F. A. Leal Yepes, T. R. Overton, A. L. Lock, S. V. Lamb, J. J. Wakshlag, and D. V. Nydam. 2016b. Effect of dry period dietary energy level in dairy cattle on volume, concentration of immunoglobulin G, insulin, and fatty acid composition of colostrum. *J. Dairy Sci.* 99:1515–1526. <https://doi.org/10.3168/jds.2015-9926>.
- Mann, S., F. A. Leal Yepes, T. R. Overton, J. J. Wakshlag, A. L. Lock, C. M. Ryan, and D. V. Nydam. 2015. Dry period plane of energy: Effects on feed intake, energy balance, milk production, and composition in transition dairy cows. *J. Dairy Sci.* 98:3366–3382. <https://doi.org/10.3168/jds.2014-9024>.
- Mann, S., D. V. Nydam, A. Abuelo, F. A. Leal Yepes, T. R. Overton, and J. J. Wakshlag. 2016c. Insulin signaling, inflammation, and lipolysis in subcutaneous adipose tissue of transition dairy cows either overfed energy during the prepartum period or fed a controlled-energy diet. *J. Dairy Sci.* 99:6737–6752. <https://doi.org/10.3168/jds.2016-10969>.
- NRC. 2001. *Nutrient Requirements of Dairy Cattle*. 7th rev. ed. National Academy Press, Washington, DC.
- Peterson, J. I., and D. S. Young. 1968. Evaluation of the hexokinase/glucose-6-phosphate dehydrogenase method of determination of glucose in urine. *Anal. Biochem.* 23:301–316. [https://doi.org/10.1016/0003-2697\(68\)90361-8](https://doi.org/10.1016/0003-2697(68)90361-8).
- Rukkwamsuk, T., T. Wensing, and M. J. Geelen. 1998. Effect of overfeeding during the dry period on regulation of adipose tissue metabolism in dairy cows during the periparturient period. *J. Dairy Sci.* 81:2904–2911. [https://doi.org/10.3168/jds.S0022-0302\(98\)75851-5](https://doi.org/10.3168/jds.S0022-0302(98)75851-5).
- Schoenberg, K. M., R. M. Ehrhardt, and T. R. Overton. 2012. Effects of plane of nutrition and feed deprivation on insulin responses in dairy cattle during late gestation. *J. Dairy Sci.* 95:670–682. <https://doi.org/10.3168/jds.2011-4529>.

- Schoenberg, K. M., and T. R. Overton. 2011. Effects of plane of nutrition and 2,4-thiazolidinedione on insulin responses and adipose tissue gene expression in dairy cattle during late gestation. *J. Dairy Sci.* 94:6021–6035. <https://doi.org/10.3168/jds.2011-4533>.
- Studer, V. A., R. R. Grummer, S. J. Bertics, and C. K. Reynolds. 1993. Effect of prepartum propylene glycol administration on periparturient fatty liver in dairy cows. *J. Dairy Sci.* 76:2931–2939. [https://doi.org/10.3168/jds.S0022-0302\(93\)77633-X](https://doi.org/10.3168/jds.S0022-0302(93)77633-X).
- Vandehaar, M. J., G. Yousif, B. K. Sharma, T. H. Herdt, R. S. Emery, M. S. Allen, and J. S. Liesman. 1999. Effect of energy and protein density of prepartum diets on fat and protein metabolism of dairy cattle in the periparturient period. *J. Dairy Sci.* 82:1282–1295. [https://doi.org/10.3168/jds.S0022-0302\(99\)75351-8](https://doi.org/10.3168/jds.S0022-0302(99)75351-8).
- Vickers, L. A., D. M. Weary, D. M. Veira, and M. A. G. von Keyserlingk. 2013. Feeding a higher forage diet prepartum decreases incidences of subclinical ketosis in transition dairy cows. *J. Anim. Sci.* 91:886–894. <https://doi.org/10.2527/jas.2011-4349>.
- Williamson, D. H., and J. Mellanby. 1974. D-3-Hydroxybutyrate. Page 1836 in *Methods of Enzymatic Analysis*. H. U. Bergmeyer, ed. Academic Press, London, UK.

ORCIDS

B. F. Richards <https://orcid.org/0000-0002-7090-6479>

K. M. Moyes <https://orcid.org/0000-0003-3591-3849>

J. K. Drackley <https://orcid.org/0000-0002-4560-5594>