Effects of Pre- and Postfresh Transition Diets Varying in Dietary Energy Density on Metabolic Status of Periparturient Dairy Cows

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ABSTRACT

Effects of dietary energy density during late gestation and early lactation on metabolic status of periparturient cows were studied. Four weeks before expected calving, animals were fed a low (DL; 1.58 Mcal of NE_L/kg) or high energy density diet (DH; 1.70 Mcal of NE_L/kg). After calving, half of the cows from each prepartum treatment were assigned to a low (L; 1.57 Mcal of NE_L/kg) or high energy density diet (H; 1.63 Mcal of NE_L/kg) until d 20 postpartum. After d 20, all animals were fed H until d 70. Animals fed DH had a more positive energy balance during the prepartum period. Animals fed DH had higher plasma concentrations of glucose and insulin and lower concentrations of plasma nonesterified fatty acid (NEFA) on d –7 relative to calving compared with animals fed DL. No differences in blood concentrations of metabolites, insulin and liver triglycerides (TG) content were observed on d 1. Liver TG content at d 1 and 21 were more related to magnitude of change in energy intake prepartum than to energy intake in the last week of gestation. Cows fed H had higher concentrations of plasma glucose and insulin, but similar plasma NEFA during the postpartum period compared with cows fed L. Plasma concentrations of β -hydroxybutyrate (BHBA) and liver TG content on d 21 were 46 and 30% lower, respectively, for cows fed H compared with cows fed L. Interactions between prepartum and postpartum treatments indicated that negative effects of delaying higher concentrate feeding until d 21 postpartum can be partially offset by increasing concentrate in the diet before calving. Cows fed L had a higher increase in white line hemorrhage scores between prepartum and 10 wk postpartum compared with cows fed H. Energy density of prepartum diets had a minor influence on metabolic status of cows postpartum. A more favorable metabolic profile occurs when increasing the concentrate content of the diet immediately postpartum compared with delaying the increase until d 21 postpartum.

(**Key words:** dairy cattle, transition, energy density, metabolic status)

Abbreviation key: DL = dry low energy density diet, DH = dry high energy density diet, L = low energy density postpartum diet, H = high energy density postpartum diet, UFA = udder floor area, TG = triglycerides.

INTRODUCTION

The transition from a dry cow to a lactating cow is characterized by metabolic and endocrine adjustments to accommodate parturition and lactation. Endocrine changes may be partially responsible for an accelerated decline in feed intake during the last 2 wk before parturition (Bertics et al., 1992). Degree of fatty acid mobilization during this period, as indicated by elevated plasma NEFA, is related to greater incidences of fatty liver and ketosis (Grummer, 1993). Increasing energy density of the diet by increasing NFC during this period may have some benefits (Grummer, 1995; Minor et al., 1998; VandeHaar et al., 1999) such as allowing ruminal microorganisms to adapt to the high concentrate diets that will be fed postpartum or decreasing fatty acid mobilization from adipose tissue and lipid-related metabolic disorders (Grummer, 1993; VandeHaar et al., 1999). However, increasing energy density of prepartum diets may lead to a greater decline of DM and energy intake as parturition approaches (Minor et al., 1998; Olsson et al., 1998b; Ingvarson and Andersen, 2000; Hayirli et al., 2002). This in turn could exacerbate the mobilization of fatty acids from adipose tissue and promote greater hepatic lipid deposition and ketone production. Following parturition, it is common to feed a diet that has less forage than the late prepartum diet, but not as high in NFC as the diet fed to cows in peak lactation. Feeding a diet with higher NFC immediately postpartum compared with delaying the increase until 3 to 4 wk postpartum may invoke similar physiological responses as those observed during prepartum.

Laminitis (pododermatitis aseptica diffusa) in cattle is a multifactorial disease of which the etiology and pathogenesis are not fully understood. Both the clinical and subclinical forms of the disease can be revealed by

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the appearance of sole hemorrhages (Bergsten, 1994; Vermunt and Greenough, 1994). The highest incidence of sole hemorrhages was found 2 to 4 mo postpartum, suggesting that feed changes close to calving induced subclinical laminitis (Bergsten, 1994; Olsson et al., 1998a).

The objective of this study was to compare the effects of dietary energy density fed during the prepartum and postpartum transition period and potential interactions between pre- and postpartum diets on metabolic status and incidence of sole hemorrhages during early lactation.

MATERIALS AND METHODS

Forty Holstein cows and 20 Holstein heifers were used in randomized complete block design to evaluate the effect of dietary energy density on periparturient dairy cattle. Cows and heifers were blocked by parity and expected calving date. A 2 × 2 factorial arrangement of treatments was used. Beginning at 28 d before expected calving, cows were fed diets with low (**DL**) or high (**DH**) energy density. After calving, half of the cows from each prepartum treatment group were assigned to a low (**L**) or high (**H**) energy density diet until d 20 postpartum. After d 20 postpartum, all cows were fed H until d 70. Details of diets, feed and milk sampling, energy calculations, BW, and BCS measurements, energy balance, and lactation performance have been previously published (Rabelo et al., 2003). Briefly, during the prepartum period (–28 d to calving), animals were fed a low energy density diet (DL; 1.58 Mcal of NE_L/kg, 40% NDF, and 38% NFC) or a high energy density diet (DH; 1.70 Mcal of NE_L/kg, 32% NDF, and 44% NFC). After calving, half of the cows from each prepartum treatment group were assigned to a low energy density diet (L; 1.57 Mcal of NE_L/kg, 30% NDF, and 41% NFC) or a high energy density diet (H; 1.63 Mcal of NE_L/kg, 25% NDF, and 47% NFC) until d 20 postpartum. After d 20, all cows were fed H until d 70. Use of the terms “high” or “low” for energy density is not meant to be relative to the NRC (2001) or diets commonly fed in the field.

Foot Scores and Udder Edema

The rear hooves of all the animals were trimmed at 4 wk before expected calving (covariate) and at 10 wk postpartum. The surface of the sole horn was photographed as described by Bergsten (1993), and a laminitis researcher who had no knowledge of the groups to which the cows belonged assessed all photographs. Each claw was assigned a score for sole and white line hemorrhages on a 4-point scale (0 to 3), which was

related to both the severity and extent of the lesions: 0 = no lesion; 1 = mild (single hemorrhagic spot or superficial hemorrhage of a small area with obvious yellowish discoloration); 2 = moderate (moderate hemorrhage on a single spot or superficial hemorrhage of a larger area); 3 = severe (profound hemorrhage on a single spot or extensive obvious hemorrhage). The scores for all 4 claws of each animal were added together.

For a quantitative evaluation of udder edema, udder floor areas (**UFA**) were measured before and after the a.m. milking (Seykora and McDaniel, 1986). Measurements were made on Monday and Thursday of each week on any cow from 0 to 11 d postpartum (i.e., 3 measurements per cow). Udder floor areas were measured by lightly placing a sheet of paper attached to a clipboard in contact with the tips of the teats immediately before and after milking. Teats were wet from milking or washing and points of contact were imprinted on the paper. The area of a trapezoid formed by imprints of the 4 teats was calculated. Percentage decrease in UFA after milking was then determined (udder shrink, % = [(UFA_{pre} – UFA_{post})/UFA_{pre}] × 100). It was assumed that the more edematous the udder, the less UFA would decrease following removal of milk.

Blood Samples and Liver Biopsies

Before the morning feeding on d 28 before expected calving and on d 1, 21, and 35 postpartum, liver samples were taken by puncture biopsy after preparation of an aseptic area and administration of a local anesthetic (10 mL of lidocaine). Liver samples were rinsed in saline, frozen in liquid nitrogen, and then stored at –20°C until determination of triglyceride (**TG**) concentrations. Samples were thawed on ice, blotted dry, and approximately 0.1 g of tissue was homogenized in 3 mL of saline. An aliquot was used for total lipid extraction by the method of Folch et al. (1957). Concentration of TG was determined using a colorimetric assay (Foster and Dunn, 1973). A second aliquot of the homogenate was used to measure DNA content of the sample (Labarca and Paigan, 1980).

Blood was sampled at 0800 h via puncture of the coccygeal vessels on d 29, 28 (covariates), and 7 before expected calving. Postpartum, blood was sampled on d 1, 7 or 8, 21, and 35. Every other day from d –9 or –8 prepartum to d 6 or 7 postpartum, additional blood was sampled for analysis of NEFA. Ten milliliters of blood was drawn into a Vacutainer containing 100 mg of potassium oxalate and 20 mg of sodium fluoride (Cat. No. L10330-00; Becton Dickinson, Franklin Lakes, NJ) and kept on ice. After centrifugation, aliquots of plasma were kept at –20°C until analyses. Enzymatic assays

Table 1. Prepartum blood metabolites and hormone concentrations of cows and heifers fed low- or high-energy diets during the prepartum period and d 1 postpartum.

Response variables	Prepartum treatments ¹		95% confidence interval (lower/upper limit) or SE		P
	DL	DH	DL	DH	
Glucose, ² mg/dL	52.0	51.9	50.4/53.7	50.2/53.7	0.95
Day -7	52.6	54.6	51.0/54.3	52.8/56.4	0.08
Day 1	51.4	49.3	48.9/54.0	46.6/52.0	0.24
Insulin, ² μ U/ml	11.7	13.2	10.7/12.8	12.1/14.5	0.05
Day -7	13.4	16.9	12.1/14.9	15.1/18.8	0.003
Day 1	10.2	10.3	9.2/11.3	9.3/11.5	0.84
NEFA, ³ μ Eq/L	254	190	221/292	166/218	0.004
BHBA, ² mg/dL	4.2	4.2	3.8/4.7	3.8/4.7	0.98
Liver TG, ⁴ μ g/ μ g of DNA	9.2	8.7	1.1	1.0	0.75

¹Prepartum treatments: DL = low-energy diet fed to dry cows or heifers; DH = high-energy diet fed to dry cows or heifers.

²Average of measurements taken on d -7 and 1 relative to calving.

³Average of measurements taken from d -8.5 to 1 relative to calving. Samples obtained every other day from d -8 or -9 prepartum to d 1 postpartum.

⁴TG = Triglyceride, measured on d 1 postpartum.

were conducted to determine concentrations of plasma glucose (Raabo and Terkildsen, 1960), BHBA (Williamson et al., 1962), and NEFA (Johnson and Peters, 1993) using commercial kits (Glucose kit no.: 510, BHBA kit no.: 310-UV, Sigma Chemical Co., St. Louis, MO; and NEFA-C kit; Wako Fine Chemicals Industries USA, Inc., Dallas, TX). Additional 10-mL blood samples were drawn into additive-free Vacutainers (Cat. No. L10262-00; Becton Dickinson) and kept at room temperature. Serum was obtained for determination of insulin concentration (Coat-a-Count; Diagnostic Products Corp., Los Angeles, CA).

Statistical Analyses

One cow calved twins and was removed from the experiment. Of 59 animals, 10 had retained fetal membranes, 4 had milk fever, 5 had ketosis, and 3 had left displaced abomasums. All blood data except glucose were log-transformed to correct for heterogeneity of variance. Udder edema and blood measurements were analyzed as repeated measures using PROC MIXED of SAS (version 8.0; SAS Institute, 1999). Two different statistical models were used according to when samples were taken. The model for samples taken during the prepartum period and through d 1 postpartum included prepartum treatment effect, block, parity, time, and 2- and 3-way interactions as fixed effects. For samples taken after d 1 postpartum, the model included prepartum and postpartum treatment effects, block, parity, time, and 2- and 3-way interactions as fixed effects. The random effect for both models was cow nested within treatment and block. Measurements obtained before administration of treatments were used as covariates

for statistical analyses of metabolic responses (blood and liver metabolites). The scores for all claws of each animal were added together. Differences in foot scores obtained 4 wk prepartum and 10 wk postpartum were analyzed using PROC MIXED of SAS (version 8.0; SAS Institute, 1999). The model included foot scores at 4 wk prepartum (covariate), prepartum and postpartum treatment effects, block, parity, and prepartum $\times$ postpartum interaction as fixed effects. The random effect was cow nested within treatment and parity. For all models, interaction terms with $P > 0.30$ were removed in a backwards stepwise manner. Least squares means and standard error of the means are reported for all data except for the majority of blood measurements. Because of the transformations to remove heterogeneity, 95% confidence intervals are reported instead of standard error of the means for the majority of blood measurements. Statistical significance was declared at $P < 0.10$ and tendency toward significance at $P > 0.10$ to $P < 0.15$.

RESULTS

Prepartum Metabolic Status

Ingredient and chemical compositions of diets fed pre- and postpartum and effects of treatments on feed intake, lactation performance, energy balance, BW, and BCS were reported previously (Rabelo et al., 2003). Increasing energy density of prepartum diets increased plasma glucose concentration on d -7 (52.6 vs. 54.6 mg/dL, DL vs. DH, respectively, $P = 0.08$; Table 1) but did not affect plasma levels on d 1 (prepartum treatment $\times$ time interaction, $P = 0.04$). Similarly, animals fed

Figure 1. Effects of prepartum treatments on plasma NEFA concentrations from samples obtained every other day from d -9 or -8 prepartum to d 1 postpartum for animals fed high energy density diets prepartum (DH) and animals fed low energy density diets prepartum (DL). Prepartum treatment and time effects were significant at $P = 0.003$ and 0.0001 , respectively. 95% Confidence intervals (lower limit/upper limit) were 166/218 and 221/292 μEq of NEFA/L for DH and DL, respectively.

DH had higher serum insulin concentrations compared with animals fed DL, but this difference was significant only on d -7 (prepartum treatment $\times$ time interaction, $P = 0.01$). Animals fed DL had higher plasma NEFA concentrations than animals fed DH on d -8.5 to 1, except for d -2.5 (Figure 1, Table 1). Although the prepartum treatment $\times$ time interaction was not significant, treatment differences in plasma NEFA concentration numerically increased as calving approached (Figure 1). No differences in plasma BHBA concentrations were observed between animals fed DH and DL on d -7 and 1 ($P = 0.98$). Liver TG content on d 1 was not affected by prepartum treatment (9.2 vs. 8.7 μg of TG/ μg of DNA for DL and DH, respectively; Table 1, $P = 0.75$).

Interactions of parity and time were significant for all blood metabolites through d 1 postpartum. Plasma NEFA concentrations were 2-fold higher for heifers compared with cows on d -8.5 (189 vs. 90 $\mu\text{Eq/L}$; Figure 2). As calving approached, plasma NEFA concentrations in heifers increased 2.5-fold, whereas for cows, a 6.6-fold increase occurred. Glucose concentrations were higher for heifers compared with cows (54.3 vs. 49.7 mg/dL, $P = 0.004$). For cows, blood glucose concentrations were lower on d 1 compared with d -7 relative to calving, whereas for heifers, glucose concentrations remained similar (parity $\times$ time interaction, $P = 0.02$). Similarly, serum insulin levels were not different between cows and heifers at d -7, but on d 1, serum insulin concentrations decreased to a greater extent in cows compared with heifers (parity $\times$ time interaction, $P = 0.005$). Parity did not affect plasma BHBA concentrations, but concentrations increased from d -7 to 1 to a greater magnitude in cows compared with heifers (par-

Figure 2. Effects of prepartum treatments on plasma NEFA concentrations from samples obtained every other day from d -9 or -8 prepartum to d 1 postpartum. Time, parity, and time $\times$ parity interactions were significant at $P = 0.001$, 0.01 , and 0.0001 , respectively. 95% Confidence intervals (lower limit/upper limit) were 161/210 and 213/320 μEq of NEFA/L for cows and heifers, respectively.

ity $\times$ time, $P = 0.09$). Liver TG content on d 1 was almost 2 times higher for cows than heifers (11.8 vs. 6.2 μg of TG/ μg of DNA, respectively; $P = 0.0001$). Energy intake or energy balance during the last week of gestation were not correlated to liver TG content on d 1 and 21 (Table 2; $P > 0.10$). Conversely, the magnitude of

Table 2. Pearson correlations (with P -values in parentheses) between prepartum energy intake, energy balance, and plasma NEFA concentrations from prepartum and d 1, and liver triglyceride (TG) content at 1 and 21 d postpartum.

Variables	Liver TG content, d 1	Liver TG content, d 21
Energy intake last week prepartum ¹		
All animals	0.05 (0.70)	0.09 (0.50)
Cows	-0.23 (0.16)	-0.31 (0.06)
Heifers	-0.28 (0.23)	0.07 (0.73)
Energy intake difference ²		
All animals	0.45 (0.0004)	0.44 (0.0007)
Cows	0.39 (0.01)	0.45 (0.006)
Heifers	0.46 (0.04)	0.32 (0.16)
Energy balance last week prepartum ¹		
All animals	0.09 (0.47)	-0.05 (0.71)
Cows	-0.25 (0.12)	-0.33 (0.05)
Heifers	-0.33 (0.16)	0.12 (0.60)
Energy balance difference ²		
All animals	0.45 (0.0004)	0.44 (0.0007)
Cows	0.38 (0.01)	0.45 (0.006)
Heifers	0.45 (0.05)	0.32 (0.17)
NEFA difference ³		
All animals	0.46 (0.0007)	0.40 (0.004)
Cows	0.43 (0.01)	0.35 (0.05)
Heifers	0.24 (0.33)	0.43 (0.06)
Liver TG content, d 1		
All animals	—	0.59 (0.0001)
Cows	—	0.61 (0.0001)
Heifers	—	0.48 (0.06)

¹Average from d -7 to -1 relative to calving.

²Difference of average values from wk -4 and d -1 relative to calving.

³Difference of values from d -8.5 and d 1 relative to calving.

Table 3. Postpartum energy balance, plasma metabolite or serum insulin concentrations, and liver triglyceride (TG) in cows fed different dietary energy densities during prepartum (Pre) and early postpartum (Post) periods.

Response variable	DL ¹		DH ¹		P-value		
	L ²	H ²	L	H	Pre	Post	Pre × Post
Energy balance, Mcal/d	-3.8 (1.0) ³	-3.8 (1.0)	-2.0 (1.0)	-3.5 (1.0)	0.33	0.47	0.45
Glucose, mg/dL	45.0 (43.1/46.9)	49.2 (47.3/51.2)	46.8 (44.8/48.7)	49.2 (47.2/51.2)	0.36	0.0014	0.35
Insulin, μ U/mL	10.2 (9.1/11.5)	13.5 (12.0/15.2)	11.8 (10.5/13.3)	13.9 (12.3/15.8)	0.13	0.0008	0.34
NEFA, μ Eq/mL	316 (264/377)	333 (279/398)	304 (255/363)	260 (216/313)	0.10	0.55	0.23
BHBA, ⁴ mg/dL							
All cows	6.7 (5.6/7.9)	4.1 (3.5/4.9)	5.9 (5.0/7.0)	4.1 (3.5/4.9)	0.45	0.0001	0.48
Primiparous	7.9 (6.0/10.4)	4.0 (3.1/5.3)	5.8 (4.4/7.6)	3.7 (2.9/4.9)	—	—	—
Multiparous	5.6 (4.6/6.8)	4.2 (3.5/5.1)	5.9 (4.9/7.2)	4.4 (3.6/5.5)	—	—	—
Liver TG, ⁵ μ g/ μ g of DNA							
All cows	10.0 (5.5/14.4)	7.2 (2.7/11.7)	10.4 (5.9/14.8)	8.1 (3.5/12.6)	0.78	0.26	0.91
Primiparous	4.3 (0/11.6)	5.9 (0/13.1)	10.2 (3.1/17.3)	9.0 (1.9/16.1)	—	—	—
Multiparous	15.6 (10.6/20.7)	8.5 (3.1/13.8)	10.5 (5.4/15.6)	7.1 (1.5/12.8)	—	—	—

¹Prepartum treatments: DL = low-energy diet fed to dry cows or heifers; DH = high-energy diet fed to dry cows or heifers.

²Postpartum treatments: L = low-energy diet; H = high-energy diet.

³Confidence intervals, 95% (lower limit/upper limit) or SE.

⁴Postpartum treatment × parity interaction ($P = 0.10$).

⁵Prepartum treatment × parity interaction ($P = 0.08$).

decreases in energy intake or balance during late gestation (difference between mean of wk -4 to d -1 relative to calving) were significantly correlated with liver TG content at d 1 and 21 postpartum. Changes in plasma NEFA concentration from d -8.5 to 1 were also significantly correlated with liver TG on d 1 and 21 (Table 2, $P < 0.01$).

Postpartum Metabolic Status

Prepartum treatments did not affect plasma glucose concentrations postpartum ($P = 0.36$; Table 3). Cows fed H had higher plasma glucose concentrations on d 7 and 21 than cows fed L, but no difference was observed on d 35 (postpartum treatment × time interaction, $P = 0.04$, Figure 3). Animals fed the DL-L sequence of treatments had the lowest plasma glucose concentration on d 7 and 21 compared with other animals, but no differences between treatments were observed on d 35, 2 wk after treatments ended (prepartum × postpartum treatment × time interaction, $P = 0.03$; Figure 3). Serum insulin tended to be higher for cows fed DH compared with cows fed DL (12.8 vs. 11.8 μ U/mL, respectively, $P = 0.13$). Cows fed H had higher serum insulin than cows fed L on d 7, 21, and 35 (mean of 13.7 vs. 11.0 μ U/mL; $P = 0.0008$). Interestingly, animals fed DH prepartum tended to have lower plasma NEFA compared with animals fed DL for samples taken after d 1 (281 vs. 325 μ Eq/mL, respectively; $P = 0.10$). Postpartum treatments did not affect plasma NEFA concentration. Plasma concentrations of BHBA were not influenced by prepartum treatments ($P = 0.45$). Plasma concentrations of BHBA were 38 and 46% lower for cows

fed H compared with cows fed L on d 7 and 21 relative to calving, respectively, but no difference was observed on d 35 (postpartum treatment × time interaction, $P = 0.007$; Figure 4). Animals fed the DL-L sequence tended to have the highest plasma BHBA concentrations on d

Figure 3. Effects of dietary treatments: low energy density diet prepartum and low energy density diet early postpartum (DL-L); low energy density diet prepartum and high energy density diet postpartum (DL-H); high energy density diet prepartum and low energy density diet postpartum (DH-L); and high energy density diet prepartum and high energy density diet postpartum (DH-H), on plasma glucose concentrations on d 7, 21, and 35 relative to calving. Interactions between postpartum treatment × time and prepartum × postpartum treatment × time were significant at $P = 0.04$ and 0.03 , respectively (SE = 1.2).

Figure 4. Plasma BHBA concentrations of cows fed low energy density diet prepartum and low energy density diet early postpartum (DL-L); low energy density diet prepartum and high energy density diet postpartum (DL-H); high energy density diet prepartum and low energy density diet postpartum (DH-L); and high energy density diet prepartum and high energy density diet postpartum (DH-H) on d 7, 21, and 35 relative to calving. Postpartum treatment $\times$ time and prepartum $\times$ postpartum treatments $\times$ time interaction were significant $P = 0.007$ and 0.12 , respectively. 95% Confidence intervals (lower limit/upper limit) were 5.6/7.9, 3.5/4.9, 5.0/7.0, and 3.5/4.9 mg/dL for DL-L, DL-H, DH-L, and DH-H, respectively.

7 and 21, but not on d 35 (prepartum $\times$ postpartum treatment $\times$ time interaction, $P = 0.12$; Figure 4). Increasing dietary energy concentration immediately after calving instead of delaying 3 wk was more effective in lowering BHBA levels in primiparous than in multiparous cows (43 vs. 26%, postpartum treatment $\times$ parity interaction, $P = 0.10$). Heifers fed DH during the prepartum tended to have higher liver TG content than those fed DL (9.6 vs. 5.1 μg of TG/ μg of DNA), whereas cows fed DH tended to have lower liver TG content than those fed DL (8.8 vs. 12.6 μg of TG/ μg of DNA, prepartum treatment $\times$ parity interaction, $P = 0.08$). Cows fed H tended to have lower TG content on d 21 than cows fed L (11.1 vs. 15.6 μg of TG/ μg of DNA, respectively, $P = 0.07$; Table 3) but no differences were observed on d 35 (4.2 vs. 4.7 μg of TG/ μg of DNA, respectively; $P = 0.84$).

Foot Scores and Udder Edema

Differences in white line and sole hemorrhage scores between the first trimming (covariate) and second trimming at 10 wk postpartum are shown in Table 4. Cows fed L during the first 3 wk postpartum had a higher increase in white line hemorrhage scores compared with cows fed H ($P = 0.01$). Animals fed the DH-L se-

quence of treatments had the highest increase in white line scores (prepartum $\times$ postpartum treatment interaction, $P = 0.04$). Differences in sole hemorrhage scores were not affected by prepartum or postpartum treatments. Neither prepartum nor postpartum treatments affected a quantitative evaluation of udder edema measured as percentage change in udder area before and after milking (Table 4).

DISCUSSION

Prepartum Energy Status

Increasing the energy density of diets fed in late prepartum period resulted in a significant increase in energy balance of animals until the day of calving (Rabelo et al., 2003). The greater increase in energy balance due to enhanced dietary energy density for cows compared with heifers might be related to greater intake capacity of cows compared with heifers (Hayirli et al., 2002; Rabelo et al., 2003). Higher concentrations of plasma glucose and insulin suggest that overall nutrient balance of animals fed DH was more positive than animals fed DL. Lower plasma NEFA concentrations for animals fed DH reflects a more favorable energy status and indicates less adipose tissue mobilization during this period. Higher concentrations of glucose (Minor et al., 1998) and insulin (Mashek and Beede, 2000; Holcomb et al., 2001), and lower concentrations of NEFA from increasing energy density of diets were previously reported (Minor et al., 1998; VandeHaar et al., 1999; Holcomb et al., 2001). Cows that were overfed during the entire dry period had lower basal lipolytic rates in adipose tissue and higher serum insulin concentration during the last week prepartum than cows that were feed restricted (Rukkwamsuk et al., 1998). Although NEFA levels were higher during the last week of gestation for animals fed DL compared with animals fed DH, no differences in liver TG on d 1 were observed. Similar results were observed by Minor et al. (1998). Conversely, VandeHaar et al. (1999), increased dietary protein and energy density during the prepartum period and observed a reduction in liver TG concentration (2.4 vs. 1.5%, wet basis) on d 1. The absence of a diet and NEFA effect on liver TG in our study suggests that the liver of animals fed DL had decreased uptake of NEFA, increased β -oxidation of NEFA, decreased esterification of NEFA, or increased export of TG from the liver or a combination of these factors.

Interactions with Parity

Higher NEFA plasma concentrations for heifers compared with cows on d -8.5 before parturition probably reflects a higher basal rate of lipolysis, a lower rate

Table 4. Differences in white line and sole hemorrhage sum of scores between the first trimming at 4 wk prepartum (covariate) and second trimming at 10 wk postpartum and udder shrink of cows fed different dietary energy densities during prepartum (Pre) and early postpartum (Post) period.

	DL ¹		DH ¹		SE	P-value		
	L ²	H ²	L	H		Pre	Post	Pre × Post
White line hemorrhage	0.43 ³	0.26	1.45	−0.08	0.33	0.30	0.01	0.04
Sole hemorrhage	0.66	0.48	1.00	0.72	0.43	0.50	0.56	0.90
Udder shrink, %	28.9	27.6	26.8	30.3	3.0	0.90	0.71	0.42

¹Prepartum treatments: DL = low-energy diet fed to dry cows or heifers; DH = high-energy diet fed to dry cows or heifers.

²Postpartum treatments: L = low-energy diet; H = high-energy diet.

³Difference of the sum of scores (0–12) between the first trimming at 4 wk prepartum (covariate) and second trimming at 10 wk postpartum.

of lipogenesis in adipose tissues, and a less favorable energy balance. Higher plasma NEFA concentrations in heifers compared with cows during the last 2 wk prepartum was observed by VandeHaar et al. (1999). Although heifers had higher NEFA concentrations at −8.5 d, the magnitude of increase in plasma as parturition approached was lower in heifers compared with cows (Figure 3). VandeHaar et al. (1999) observed a similar pattern. The absence of abrupt changes in concentrations of plasma metabolites and serum insulin as parturition approached probably reflects the lower magnitude of energy balance depression in heifers compared with cows (Rabelo et al., 2003). Because of the lower DMI and extra requirements for growth, average energy intake for heifers during the last 4 wk before parturition was 6% above requirements, whereas for cows it was 55% above requirements. A relatively small drop in circulating glucose during early lactation in animals feed-restricted to meet energy requirements during the dry period, compared with animals fed ad libitum (Kunz et al., 1985) suggested improved glucose homeostasis. Cows that were fed ad libitum during the last 3 wk of gestation had a more sudden increase in plasma NEFA as parturition approached compared with feed-restricted cows (Holcomb et al., 2001).

Relatively small changes in NEFA concentrations and energy intake before calving might be responsible for the lower liver TG content observed in heifers compared with cows. Significant positive correlations between changes in NEFA concentration around calving and liver TG content on d 1 and 21 relative to calving support this hypothesis. Feed-restricting (80% of NEL requirements) cows from dry-off (60 d before predicted calving date) increased prepartum NEFA concentrations and decreased liver TG concentrations on d 1 compared with cows fed ad libitum (Douglas et al., 1998). The magnitude of DMI decrease for the restricted group in this study was lower compared with cows fed ad libitum. Higher basal rates of lipolysis in heifers, as suggested by higher plasma NEFA, might lead to a

well-adapted liver for metabolism of fatty acids at parturition (Rukkwamsuk et al., 1998). Higher NEFA concentrations in heifers might have stimulated total β -oxidation and lowered hepatic TG accumulation (Grum et al., 1996).

In vitro rates of lipolysis were stimulated more by noradrenaline in adipose tissue obtained from periparturient cows overfed during the dry period compared with feed-restricted cows (Rukkwamsuk et al., 1998). Additionally, the in vitro lipolytic response tended to be less inhibited by glucose or 3-hydroxybutyrate in adipose tissue obtained from overfed cows compared with feed-restricted cows (Rukkwamsuk et al., 1998). The greater magnitude of change in plasma NEFA concentrations observed in cows compared with heifers might be due to their overfed state and a greater predisposition to mobilize more fatty acids from adipose tissue, contributing to greater TG accumulation in the liver after parturition.

Postpartum Energy Status

Increasing prepartum diet energy concentration had minor effects on overall postpartum blood metabolites, in agreement with other studies (VandeHaar et al., 1999; Mashek and Beede, 2000). Feeding cows H during the first 3 wk of lactation promoted a more vigorous fermentation, as indicated by a lower pH and higher concentration of propionate in the rumen (Rabelo et al., 2003). Higher concentrations of rumen propionate, a major glucogenic precursor and a potent insulin secretagogue, might have been responsible for the higher glucose and insulin concentrations in cows fed H compared with cows fed L. Although cows fed H had higher glucose and insulin concentrations, NEFA concentrations did not differ, suggesting the antilipolytic effects of insulin did not occur. Although feeding H failed to decrease NEFA concentrations, it caused a 30% reduction in liver TG and a 48% decrease in BHBA concentrations on d 21 compared with feeding L. This suggests

a direct effect of propionate, insulin, or both on hepatic lipid metabolism. An antiketogenic effect is likely (Drackley et al., 2001); effects of propionate and insulin on bovine hepatic TG synthesis and secretion have not been studied. By increasing starch fermentability in the rumen through sorghum grain processing, Santos et al. (2000) were able to improve energy status of cows during early lactation and increase plasma glucose and insulin. Minor et al. (1998) observed improved milk production and higher plasma glucose and lower NEFA and BHBA concentrations in animals fed diets high in NFC compared with animals fed diets low in NFC. However, in their study, effects of prepartum and postpartum treatments could not be differentiated.

The prepartum $\times$ postpartum treatment interactions observed for glucose and BHBA concentrations on d 7 and 21 indicated that the DL-L sequence of treatments resulted in cows in the poorest energy status during the first 3 wk of lactation. The negative effects of delaying higher concentrate feeding until d 21 postpartum may be partially offset by increasing concentrate feeding before calving.

Subclinical laminitis is common in periparturient confinement-housed dairy cows (Bergsten, 1994). Hemorrhages on the cleaned sole of a cow are considered an indicator of subclinical laminitis. Both acute and subclinical forms of laminitis are thought to have nutritional and environmental components. Laminitis has been observed subsequent to acute and subacute acidosis. Ruminal acidosis causes the release of specific toxic factors (Mullenax et al., 1966) or vasoactive substances incriminated in the pathogenesis of laminitis. Results from evaluation of white line hemorrhage scores in this trial suggest that increasing concentrate immediately after calving instead of delaying it to 3 wk postpartum has positive effects on hoof health. Higher ruminal concentrations of butyrate and particularly propionate in cows fed H compared with L (Rabelo et al., 2003) might have increased papillae length (Rabelo et al., 2001), increased absorption rate of VFA, and led to less accumulation of VFA and, consequently, fewer cases of subclinical acidosis and laminitis.

The quantitative evaluation of udder edema indicated no effects of prepartum or postpartum diets or parity. Increasing concentrate feeding before parturition was associated with increased udder edema in some studies (Emery et al., 1969; Johnson and Otterby, 1981), but not in others (Fountain et al., 1949; Hathaway et al., 1957; Greenhalgh and Gardner, 1958; Schmidt and Schultz, 1959; Mashek and Beede, 2000). The higher incidence of udder edema in some studies with increasing concentrate feeding is probably related to excessive intake of other nutrients (e.g., sodium, potassium) rather than concentrate feeding per se. Exces-

sive intakes of sodium and potassium were implicated as causative agents in udder edema (Randall et al., 1974). The increased edema observed in heifers fed 7 to 8 kg/d of concentrate compared with no concentrate during the last 3 wk of gestation (Emery et al., 1969) probably resulted from 1% mineralized salt in the grain mix.

CONCLUSIONS

The findings of the current study suggest that energy density of prepartum diets has a minor influence on postpartum metabolic status of cows compared with energy density of diets fed during the first 3 wk of lactation. A more favorable metabolic profile occurs when increasing the concentrate content of the diet immediately postpartum compared with delaying the increase until d 21 postpartum. A more favorable profile was considered to be lower plasma concentrations of BHBA, lower liver TG content, and higher plasma concentrations of glucose and insulin. Interaction between prepartum and postpartum treatments indicate that the negative effects of delaying higher concentrate feeding until d 21 postpartum may be partially offset by increasing concentrate feeding before calving. Increasing energy density of prepartum diets was not associated with increased udder edema. Hoof health seems to be improved by increasing the concentrate content of the diet immediately postpartum compared with delaying the increase until d 21 postpartum.

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