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Effects of prepartum dietary protein level and feed intake on postpartum lactation performance and feeding behavior of multiparous Holstein dairy cows

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ABSTRACT

An experiment was conducted to determine the effects of low and high metabolizable protein (MP) diets when fed for ad libitum and controlled intake during the prepartum period on postpartum lactation performance and feeding behavior of dairy cows. Thirty-six multiparous Holstein cows were blocked by parity, expected calving date, and previous lactation milk yield at −21 d relative to expected calving and were randomly assigned to 1 of 4 close-up period dietary treatments providing low MP (LMP) or high MP (HMP) diets with controlled intake (CNI) or ad libitum intake (ALI). The concentrations of MP were 65 and 90 g/kg dry matter for LMP and HMP diets, respectively, whereas intake was controlled to supply 100 and 160% of the NRC (2001) energy requirements for CNI and ALI groups, respectively. The concentration of net energy for lactation (NE_L) in the treatment diets was 1.50 Mcal/kg. All cows were fed a similar lactation diet after calving (1.50 Mcal/kg of NE_L and 83.3 g/kg of MP). The HMP diet increased dry matter intake during the first 3 wk and tended to increase dry matter intake over the 9 wk of lactation. Meal size and eating rate increased in the ALI cows during the prepartum period. Meal frequency increased with the HMP diet during the postpartum period. Milk yield increased by 15.2% with the HMP diet over the 9 wk of lactation. The HMP diet increased energy-corrected milk (ECM) yield in CNI versus ALI cows, whereas the LMP diet increased ECM yield in ALI versus CNI cows over the 9 wk of lactation. The increase in ECM yield of LMP-ALI versus LMP-CNI cows was supported by greater body condition loss and serum β-hydroxybutyrate over the 9 wk of lactation. Taken together, these data indicate that prepartum controlled intake of a high protein diet can provide the benefits of both strategies.

Key words: transition cow, metabolizable protein, energy intake, feeding behavior, milk yield

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INTRODUCTION

Dairy cows are subjected to several challenges around parturition that can affect their future lactation performance. Insufficient adaptation or failure to adapt to these changes results in severe productive and health issues at the farm level (Cardoso et al., 2020). The formulation and delivery of appropriate diets are paramount for successful transition from the nonlactating to lactating period. The potential health benefits of the prepartum controlled energy strategy were observed in several studies (Dann et al., 2006; Graugnard et al., 2013; Mann et al., 2015). Controlling prepartum energy intake to 80 and 100% of the NRC (2001) requirements has been shown to increase postpartum DMI while reducing postpartum fat mobilization and consequent health disorders in dairy cows (Douglas et al., 2006; Janovick et al., 2011). Moreover, literature studies also indicate that feeding prepartum dietary energy ≥125% of the NRC (2001) recommendation could result in more prepartum adipose fat deposition, low postpartum DMI, and elevated BHB levels during early lactation, thereby increasing the risk of subclinical or clinical ketosis (Cardoso et al., 2020). However, in a few studies, energy restriction through controlled DMI has been shown to decrease milk yield by 13 to 20% (Douglas et al., 2007; Janovick and Drackley, 2010; Urdl et al., 2015), which could be associated with the parallel restriction of protein supplies in such diets (Douglas et al., 2007; Janovick and Drackley, 2010; Graugnard et al., 2012). In the literature, approximately 21 kg of body protein could be mobilized between −2 and +5 wk relative to calving (Komaragiri and Erdman, 1997; Phillips et al., 2003). Moreover, studies show that this mobilization is limited to the first 2 to 3 wk of lactation (Doepel et al., 2002; van der Drift et al., 2012).

Feeding a high protein diet during the prepartum period primarily aims to reduce prepartum protein mobilization to supply AA for postpartum protein synthesis and gluconeogenesis (Bell et al., 2000; Stockdale and Roche, 2002; Kokkonen, 2014). The dietary MP of 800 g/d (~66 g/kg of DM) is recommended for prepartum multiparous cows (NRC, 2001; Husnain and Santos, 2019). However, the results of various studies showed an increase in the milk yield of multiparous dairy cows from 8.20 to 11.4% when prepartum dietary MP supplies were increased from 778 to 1,316 g/d (Huyler et al., 1999; Phillips et al., 2003; Amirabadi Farahani et al., 2017). Furthermore, the protein requirements of dairy cows during late gestation (NRC, 2001; Husnain and Santos, 2019) were established using studies where energy supplies were 133% to 183% of the NRC (2001) recommendation. Alternatively, the studies (Vandehaar et al., 1999; Doepel et al., 2002) where both dietary MP (850 to 1,635 g/d) and energy density (100% to 147%) were modified showed no benefit on the postpartum performance of dairy cows, most likely because these studies were conducted under ad libitum feeding before the concept of energy restriction through controlled feed intake was introduced (Douglas, 2002).

Thus, it is also important to understand the interaction between protein and energy supplies through restricted versus ad libitum intake during the prepartum period. In the present study, we hypothesized that providing prepartum cows with an increased level of protein and controlled energy would improve DMI, serum free fatty acid (**FFA**), and BHB concentrations, and increase milk production during the postpartum period. Therefore, the objective of this study was to investigate the effects of ad libitum (160%) and controlled (100%) intake (NRC, 2001) of diets with low (65 g/kg of DM) and high MP supplies (90 g/kg of DM) during prepartum on (1) postpartum DMI, milk production, and milk composition; (2) periparturient feeding behavior; and (3) changes in BW, BCS, and metabolic status of multiparous Holstein cows.

MATERIALS AND METHODS

Cows

This study was conducted at a USDA-funded Holstein dairy research unit (Training and Research Demonstration Farm), University of Veterinary and Animal Sciences, Ravi Campus (31.02°N, 73.85°E, and 186 m altitude; Pattoki, Pakistan). The entire study was conducted under the protocols approved by the ethical committee for animal welfare at the University of Veterinary and Animal Sciences. Thirty-six multiparous Holstein cows dried off at 60 d before expected date of parturition were enrolled in this study. At dry-off, there were no differences among prepartum treatment groups for (mean ± SD) parity (2.89 ± 0.87), gestation period length (271 ± 3.57 d), previous lactation yield for 240 d (5,712 ± 1,095 kg), calving interval (397 ± 44.6 d), age at current calving (51.0 ± 12.1 mo), previous lactation length (337 ± 44.6 d), BW (620 ± 65.0 kg), and BCS (3.28 ± 0.22). The prepartum treatment period was conducted from August 20, 2019, through October 29, 2019.

Experimental Design, Treatments, and Feeding

Cows were fed a similar far-off diet once daily (0600 h) for ad libitum intake (Table 1). Cows were moved to individual pens and switched to the respective dietary treatments at −21 d relative to expected parturition and were maintained on these diets until parturition. All cows had free access to their respective diets and all the pens were equal in size, design, flooring, bunk space, and water accessibility. Cows were enrolled and blocked following these characteristics: (1) parity, (2) previous lactation yield, and (3) expected date of parturition. Cows in each block were randomly assigned to 1 of 4 prepartum dietary treatments in a 2 × 2 factorial arrangement; high MP ad libitum intake (**HMP-ALI**), high MP controlled intake (**HMP-CNI**), low MP ad libitum intake (**LMP-ALI**), and low MP controlled intake (**LMP-CNI**). The supplies of MP were 65 and 90 g/kg of DM for LMP and HMP groups, respectively. Intake was controlled to supply 100 and 160% of the NRC (2001) energy requirements for CNI and ALI groups, respectively. The DMI was restricted to 80% of the predicted DMI in CNI cows to achieve 100% of the NRC (2001) energy requirements. Diets were formulated using the NRC (2001) model. Ingredient and chemical composition of the treatment diets is presented in Table 1. The energy and MP supplies and balances were estimated using the NRC (2001) model, by using actual BW, BCS, milk yield, and milk composition, and based on actual chemical composition of the individual feed ingredients. Diets were designed to provide 2 different MP levels with low and high MP:NE_L ratios (43 and 60 g/Mcal of DM, respectively). Treatment diets during prepartum were fed twice daily with half of the diet at 0600 h and the remainder at 1800 h. Postpartum data were collected over the 9 wk of lactation and all cows were fed a similar lactation diet for ad libitum intake.

Table 1. Ingredients and chemical composition of far-off, close-up, and lactation diets

Item	Far-off	Close-up period diet[1] LMP	HMP	Lactation
Ingredient, % of DM				
Oat silage	48.1	34.0	34.0	41.8
Wheat straw	12.2	19.8	16.0	8.37
Corn grain	15.7	25.0	14.0	25.2
Canola meal	14.9	8.00	23.0	14.7
Wheat bran	4.37	8.00	8.00	4.19
Molasses cane	3.50	3.00	3.00	4.19
Mineral premix[2]	0.06	0.06	0.06	0.42
Magnesium oxide	0.44	0.05	0.05	0.21
Trace minerals[3]	0.09	0.005	0.005	0.02
Mycotoxin adsorbent[4]	0.006	0.005	0.005	0.02
Yeast[5]	0.005	0.005	0.005	0.02
Biotin	0.002	0.002	0.002	0.008
Dicalcium phosphate	0.05	0.05	0.05	0.20
Anionic premix[6]	—	2.07	1.86	—
Calcium carbonate	0.61	—	—	0.63
MetaSmart[7]	—	—	—	0.09
Analyzed nutrient composition				
% DM	46.0	53.8	53.8	48.1
OM, % of DM	95.0	93.3	93.6	94.2
CP, % of DM	12.6	9.90	14.6	12.6
NDF, % of DM	46.0	43.0	43.6	39.8
ADF, % of DM	29.0	26.7	27.5	24.8
NFC, % of DM	31.7	37.1	31.8	38.2
Ether extract, % of DM	3.50	3.30	3.60	3.60
Predicted nutritive value[8]				
MP, g/kg of DM	80.7	65.0	90.0	83.3
RUP, % CP	33.3	32.3	32.2	38.1
RDP, % CP	66.7	67.7	67.8	61.9
ME, Mcal/kg of DM	2.37	2.42	2.41	2.38
NE_L, Mcal/kg of DM	1.48	1.50	1.50	1.50
DCAD, mEq/kg	25.4	−3.00	−3.00	21.8
MP:NE_L, g/Mcal of DM	54.5	43.0	60.0	55.5

[1]LMP = 65 g/kg MP of DM and HMP = 90 g/kg MP of DM offered for ad libitum intake (ALI) to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation and controlled intake (CNI) to restrict NE_L intake to 100% of the NRC (2001) recommendation.

[2]Contained 0.05% Ca, 0.55% P, 1.58% Mg, 0.77% K, 0.18% S, 0.03% Na, 0.09% Cl, 2.4% Zn, 0.63% Cu, 1.5% Mn, 0.01% Se, 0.008% Co, 0.02% I, 2,000 IU/g of vitamin A, 750 IU/g of vitamin D, and 10 IU/g of vitamin E.

[3]Bioplex, Alltech. Organic trace minerals contained (mg/kg of DM): zinc (62,500), copper (10,000), manganese (40,000), iodine (4,000), selenium (300), cobalt (1,250), and chromium (200).

[4]Mycosorb, Alltech. Glucomannan mycotoxin adsorbent.

[5]*Saccharomyces cerevisiae* fermentation product (XPC, Diamond V).

[6]Contained 9.57% S, 9.90% Cl, 12.2% Ca, 4.10% P, 2.62% Mg, 0.43% Zn, 0.21% Fe, 0.05% Mn, 0.04% Cu, 0.003% I, 0.001% Se, 0.0005% Co, 150 IU/g vitamin A, 45 IU/g vitamin D, and 1.05 IU/g vitamin E.

[7]MetaSmart dry (Adisseo Inc.).

[8]Predicted using NRC (2001) model.

The postpartum diet was offered thrice daily at 0630, 1330, and 2030 h. All cows had free access to fresh drinking water throughout the day.

Measurements, Sampling, and Analyses

All the diets were fed as TMR to each cow individually after mixing in a FMV-5S mixer feeder (Fimaks Makina). Individual feed offered and feed refused were recorded daily from the initiation of prepartum treatments through 63 d postpartum. Moisture content of the individual ingredient was determined on a weekly basis and used to make ration adjustments. Ingredients were sampled weekly, oven-dried until constant weight was achieved (Memmert 600), and composited monthly to analyze for composition. The samples were ground through a 1-mm screen (Wiley mill, Arthur H. Thomas Co.) and were subjected to the analysis of ether extract (method 920.39), CP (method 984.13, N × 6.25; Kjeldahl method), and ash (method 942.05) contents following the standard procedures of AOAC International (2005). The concentrations of NDF (α-amylase + sodium sulfite treated filtration) and ADF (sulfuric acid + cetyltrimethylammonium bromide treated filtration) were determined sequentially according to Van Soest et al. (1991) by using Ankom-2000 fiber analyzer (Ankom Technology Corp.). Farm employees and laboratory staff were blinded to treatment assignments throughout the study.

Cows were milked thrice daily at 0600, 1300, and 2000 h (GEA WestfaliaSurge GmbH). Daily milk production was recorded electronically for each cow via the herd management system Dairy Plan C21 (GEA Farm Technologies GmbH). Samples of total milk for each cow were obtained weekly through automatic milk samplers during each milking (DemaTron 70, GEA WestfaliaSurge GmbH). Aliquots of each milking were composited in proportion to the respective milk yield to achieve representative samples. Milk samples of each cow were collected weekly and analyzed with an ultrasonic milk analyzer (Lactoscan S, Milkotronic) for fat, protein, and lactose contents.

Body weights of the cows were recorded weekly after morning milking and before feed distribution. Body condition score was measured once per week (Edmonson et al., 1989) independently by 3 individuals throughout the experiment and median score was used for each cow. Blood samples were taken 4 h after morning feeding from the coccygeal blood vessels using evacuated tubes without additive at d −21, −14, −7, −3, 3, 7, and weekly afterward until d 63 relative to parturition. Serum samples were collected following centrifugation at 2,000 × g for 15 min at 4°C and were stored at −20°C for later analysis. Serum samples were analyzed following the methods described previously (Maillo et al., 2012; Amanlou et al., 2017) using commercially available enzymatic kits (Randox Laboratories Ltd.) for the concentrations of glucose (GL2623), BUN (UR107), FFA (FA115), BHB (RB1007), triglyceride (**TG**; TR210), and cholesterol (CH201) using a biochemical analyzer (RX Monza, Randox Laboratories Ltd.).

Feeding Behavior

All cows were equipped with electronic data loggers to observe the feeding behavior of the enrolled cows (Nedap SmartTag Neck; Nedap Livestock Management). These loggers measured the accelerated movements in a particular direction and specific head positions through a G-sensor based on a 3-dimensional accelerometer. All the measurements were classified as eating per second by using acceleration as the measure of movement as validated (Borchers et al., 2021) and reported previously (Hut et al., 2021). An antenna attached in the shed received the sensor information, the data were transferred to a cloud-based storage through an on-farm process controller, and specified feeding behavior was detected through a proprietary neural network (Hut et al., 2021). Before starting data collection, the cows were provided a minimum 7-d period after attachment of data loggers. In general, feeding visits are grouped into meals, but no broadly accepted definition of meal exists. Previous reports used meal criteria ranging from 2 to more than 40 min (Tolkamp et al., 2000). The meal criterion was estimated by distribution of intervals between visits using the mixed distribution method described by Tolkamp and Kyriazakis (1999) and a meal criterion of 8 min was used. Meal size was defined as kilograms of DMI in each meal, whereas eating rate was defined as daily intake of DM as grams per minute of total eating time.

Calculations

Changes in BCS and BW for pre- and postpartum periods were calculated from wk −3 through wk −1 relative to parturition and wk 1 through wk 9 of lactation, respectively. Nonfibrous carbohydrates were determined by NFC = 100 − (CP + NDF + ether extract + ash) according to NRC (2001). Energy-corrected milk was calculated from ECM = [0.327 × milk (kg)] + [12.95 × fat (kg)] + [7.65 × true protein (kg)] following Tyrrell and Reid (1965) and protein-corrected milk (**PCM**) was calculated as follows: 3.4% PCM = milk (kg/d) × 0.294% CP, as described by Charbonneau et al. (2006). Energy balance (both pre- and postpartum) was calculated for each cow using equations from NRC (2001). Net energy intake (NE_I in Mcal) was calculated by multiplying the daily DMI by the calculated NE_L density of the diet. Net energy requirement for maintenance (NE_M in Mcal) was calculated as $BW^{0.75} \times 0.08$. Net energy requirement for pregnancy (NE_P in Mcal) was calculated as $[(0.00318 \times \text{d of gestation} - 0.0352) \times \text{calf birth weight}/45)]/0.218$. Net energy required for milk production (NE_L in Mcal) was calculated as $(0.0929 \times \text{fat \%} + 0.0563 \times \text{protein \%} + 0.0395 \times \text{lactose \%}) \times \text{milk yield}$. Prepartum energy balance was calculated as $EB_{pre} = NE_I - (NE_M + NE_P)$ and postpartum energy balance was calculated as $EB_{post} = NE_I - (NE_M + NE_L)$.

Statistical Analyses

Data collected on daily basis were condensed to weekly means before the statistical analysis. Prepartum data were limited to −21 d relative to actual parturition. Prepartum data and postpartum data from wk 1 to 3 and wk 1 to 9 of lactation were analyzed separately. Experimental data were analyzed as a completely randomized block design in a 2 × 2 factorial arrangement of the treatments. All cows were included in the statistical analysis. Repeated-measures analysis was conducted for variables measured over time (DMI, BW, BCS, milk yield, milk composition, feeding behavior, and blood metabolites). Week was considered as a repeated measure. However, for 3-wk pre- and postpartum periods, week was replaced with day for intake, feeding behavior, and milk yield data; therefore, the effects of day or week are presented as time (**T**). Repeated-measures data were analyzed using PROC GLIMMIX of SAS University Edition (SAS Institute Inc.). Statistical model included fixed effects of dietary MP level, controlled or ad libitum intake (**I**), T as day or week, MP × I interaction, MP × T interaction, I × T interaction, and MP × I × T interaction. The random error term used for all models was cow within MP and intake level and the covariance structure yielding the lowest Akaike's information criterion was used (Littell et al., 1998). Using this methodology, an autoregressive covariance structure was the best fit for all data in the current experiment. Degrees of freedom were calculated using Satterthwaite option. The GLIMMIX procedure of SAS was used without repeated measure statement and week relative to calving, and associated interactions were also removed from the model for variables not measured over time (BW change, BCS change, days on treatment, and cumulative milk yield). Data are reported as least squares means, and statistical significance was declared at $P \leq 0.05$ and trend toward significance was declared at $0.05 < P \leq 0.10$ using the Tukey's multiple comparison test.

RESULTS

DMI

Effects of prepartum dietary treatments on intake of DM, MP, and NE_L during the pre- and postpartum periods are presented in Table 2. The numbers of days on prepartum dietary treatments were not different among the treatment groups and averaged 22.4 d ($P > 0.10$). The prepartum dietary MP level did not affect prepartum DMI ($P > 0.10$). The postpartum DMI increased during the first 3 wk of lactation ($P = 0.01$) and tended to increase over the 9 wk of lactation ($P = 0.06$) in cows fed HMP diet during the prepartum period. The prepartum HMP diet increased MP ($P = 0.03$) and NE_L ($P = 0.01$) intake during the first 3 wk postpartum and increased NE_L intake over the 9 wk postpartum ($P = 0.01$). As designed, the DMI and NE_L intake during the prepartum period were lower in CNI versus ALI cows ($P < 0.01$). The energy supply met 105% of the requirements for CNI cows and 165% of the requirements for ALI cows during the prepartum period ($P < 0.01$). Postpartum DMI, NE_L intake, and EB did not differ between prepartum CNI and ALI cows ($P > 0.10$). An interaction of MP × I was observed for prepartum MP intake, such that increase in MP intake in ALI cows compared with CNI cows was greater when fed HMP versus LMP diet ($P < 0.01$). An I × T interaction was observed on MP intake and energy balance, as both decreased in ALI cows only, as calving approached ($P = 0.03$). After calving, the DM, MP, and NE_L intake, and energy balance increased in all cows with increasing DIM over the 9 wk of lactation (T, $P < 0.01$).

Feeding Behavior

Effects of prepartum dietary treatments on periparturient feeding behavior of dairy cows are presented in Table 3. Prepartum meal frequency increased by 16.7% in the cows fed HMP diet ($P = 0.04$). Meal length ($P = 0.07$), meal size ($P = 0.06$), and intermeal interval ($P = 0.10$) tended to decrease with HMP diet during the prepartum period. Prepartum total eating time, eating min/kg of DM, and eating rate were not affected by dietary MP level ($P > 0.10$). After parturition, meal frequency increased by 11.8% ($P = 0.02$) and intermeal interval decreased by 12.2% ($P = 0.03$) with HMP diet over the 9 wk of lactation. The ALI cows had 34.9% increase in meal size, 31.6% increase in eating rate, and 25.3% decrease in eating min/kg of DM than CNI cows during the prepartum period ($P \leq 0.03$). Prepartum feed intake had no effects on prepartum total eating time, meal frequency, meal length, intermeal interval, and postpartum feeding behavior variables over the 9 wk of lactation ($P > 0.10$). As calving approached, meal length, intermeal interval, and meal size decreased in all cows (T, $P \leq 0.05$), whereas meal frequency increased (T, $P < 0.01$). Total eating time, meal length, intermeal interval, meal size, and eating min/kg of DM increased in all cows, whereas meal frequency and eating rate decreased as lactation progressed over the 9 wk of lactation (T, $P \leq 0.05$).

Milk Yield and Composition

Effects of prepartum dietary treatments on milk yield and composition are presented in Table 4. Prepartum dietary MP levels did not affect milk yield for the first 3 wk postpartum ($P > 0.10$). The cows fed the HMP diet prepartum produced 15.2% more milk over the 9 wk of lactation than those fed the LMP diet ($P = 0.05$).

Table 2. Effects of prepartum intake and dietary MP level on DM, protein, and energy intake

	Close-up period treatment[1]					P-value[2]							
	HMP		LMP										
Item	ALI	CNI	ALI	CNI	SEM	MP	I	T	MP × I	MP × T	I × T	MP × I × T
Prepartum												
Days on treatment	20.7	22.7	22.0	22.9	1.24	0.57	0.23	—	0.64	—	—	—
DM, kg/d	13.8	9.15	13.9	9.15	0.067	0.44	<0.01	0.38	0.43	0.61	0.16	0.71
MP, g/d	1,258	823	902	593	5.1	<0.01	<0.01	0.28	<0.01	0.62	0.03	0.78
NE_L, Mcal/d	20.8	13.8	20.7	13.6	0.10	0.13	<0.01	0.39	0.74	0.61	0.16	0.72
EB,[3] Mcal/d	8.30	0.62	8.00	0.43	0.382	0.50	<0.01	<0.01	0.88	0.71	0.03	0.99
Postpartum												
Wk 1–3												
DM, kg/d	20.8	21.1	20.3	19.9	0.31	0.01	0.96	<0.01	0.20	0.99	0.70	0.76
MP, g/d	1,721	1,755	1,685	1,650	29.1	0.03	0.97	<0.01	0.24	0.99	0.58	0.75
NE_L, Mcal/d	31.1	31.7	30.5	29.9	0.47	0.01	0.96	<0.01	0.20	0.99	0.70	0.76
EB, Mcal/d	7.46	5.40	4.93	7.70	1.357	0.93	0.79	0.15	0.08	0.65	0.30	0.85
Wk 1–9												
DM, kg/d	21.2	21.5	20.8	20.6	0.30	0.06	0.80	<0.01	0.42	0.81	0.62	0.79
MP, g/d	1,759	1,788	1,723	1,706	27.2	0.26	0.85	<0.01	0.54	0.81	0.62	0.79
NE_L, Mcal/d	31.8	32.3	31.2	30.9	0.40	0.01	0.76	<0.01	0.34	0.81	0.64	0.80
EB, Mcal/d	7.23	5.83	7.35	7.49	1.029	0.37	0.53	0.05	0.44	0.48	0.62	0.16

[1]LMP = 65 g/kg MP of DM and HMP = 90 g/kg MP of DM offered for ad libitum intake (ALI) to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation and controlled intake (CNI) to restrict NE_L intake to 100% of the NRC (2001) recommendation from −21 d relative to expected parturition until parturition.

[2]Probability of treatment effects: MP = effects of prepartum dietary MP level, HMP versus LMP diets; I = effects of prepartum feed intake, ALI versus CNI; T = effects of time relative to calving (in days for 3-wk pre- and postpartum periods and in weeks for 1–9 wk of lactation).

[3]EB = energy balance.

Table 3. Effects of prepartum intake and dietary MP level on feeding behavior

	Close-up period treatment[1]					*P*-value[2]						
	HMP		LMP									
Item	ALI	CNI	ALI	CNI	SEM	MP	I	T	MP × I	MP × T	I × T	MP × I × T
Prepartum												
Eating time, min/d	270	213	239	230	26.9	0.76	0.20	0.14	0.34	0.06	0.95	0.21
Meal frequency, no./d	12.5	10.3	9.93	9.60	0.857	0.04	0.11	<0.01	0.22	0.28	0.85	0.29
Meal length, min/meal	21.4	21.5	24.3	24.8	1.83	0.07	0.85	0.04	0.93	0.35	0.57	0.79
Meal size, kg of DM/meal	1.10	0.91	1.41	0.95	0.095	0.06	<0.01	<0.01	0.10	0.12	0.97	0.12
Eating min/kg of DM	19.5	23.6	17.0	25.3	2.35	0.83	<0.01	0.09	0.31	0.12	0.93	0.40
Intermeal interval, min	95.0	125	130	140	16.71	0.10	0.20	<0.01	0.52	0.15	0.99	0.09
Eating rate, g/min	51.7	43.0	57.5	40.0	6.25	0.81	0.03	0.45	0.45	0.32	0.89	0.13
Postpartum												
Wk 1–3												
Eating time, min/d	299	251	232	278	28.9	0.49	0.96	<0.01	0.11	0.04	0.97	0.92
Meal frequency, no./d	14.7	13.0	12.4	12.3	0.80	0.06	0.29	<0.01	0.34	0.06	0.72	0.57
Meal length, min/meal	20.1	19.5	18.5	22.1	1.40	0.70	0.27	<0.01	0.13	0.54	0.51	0.10
Meal size, kg of DM/meal	1.41	1.65	1.64	1.64	0.117	0.34	0.27	0.01	0.30	0.25	0.67	0.60
Eating min/kg of DM	14.6	11.6	11.5	13.8	1.39	0.82	0.77	0.02	0.06	0.02	0.97	0.86
Intermeal interval, min	80.8	94.5	100	98.5	11.16	0.29	0.59	0.01	0.48	0.30	0.71	0.70
Eating rate, g/min	69.3	84.6	86.6	71.9	15.46	0.88	0.98	<0.01	0.33	0.46	0.29	0.44
Wk 1–9												
Eating time, min/d	326	311	273	320	32.8	0.52	0.63	<0.01	0.37	0.63	0.59	0.69
Meal frequency, no./d	13.5	13.0	12.2	11.5	0.58	0.02	0.29	0.02	0.84	0.20	0.19	0.50
Meal length, min/meal	24.2	24.5	22.5	28.3	2.05	0.58	0.14	<0.01	0.18	0.53	0.19	0.93
Meal size, kg of DM/meal	1.57	1.67	1.70	1.81	0.097	0.15	0.26	<0.01	0.96	0.54	0.54	0.63
Eating min/kg of DM	15.5	14.4	13.1	15.5	1.21	0.57	0.56	<0.01	0.15	0.38	0.45	0.64
Intermeal interval, min	84.6	90.3	98.2	101	5.23	0.03	0.43	0.02	0.74	0.18	0.37	0.58
Eating rate, g/min	64.7	69.6	76.5	64.5	8.41	0.68	0.66	<0.01	0.31	0.52	0.42	0.83

[1]LMP = 65 g/kg MP of DM and HMP = 90 g/kg MP of DM offered for ad libitum intake (ALI) to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation and controlled intake (CNI) to restrict NE_L intake to 100% of the NRC (2001) recommendation from −21 d relative to expected parturition until parturition.

[2]Probability of treatment effects: MP = effects of prepartum dietary MP level, HMP versus LMP diets; I = effects of prepartum feed intake, ALI versus CNI; T = effects of time relative to calving (in days for 3-wk pre- and postpartum periods and in weeks for 1–9 wk of lactation).

The ECM yield tended to increase by 13.8% with the HMP diet compared with the LMP diet over the 9-wk period ($P = 0.06$). The CNI cows had 12.8% greater ECM yield than ALI cows fed the HMP diet, whereas the ALI cows had 9.13% greater ECM yield than CNI cows fed LMP diet over the 9 wk of lactation (Figure 1), leading to a 3-way interaction of MP × I × T ($P = 0.05$). The yield of 3.4% PCM tended to increase with the HMP diet ($P = 0.09$). The cumulative milk yield over the 63-d period increased by 15.1% with the HMP versus LMP diet ($P = 0.04$). Prepartum feed intake had no effect on milk yield during the first 9 wk of lactation ($P > 0.10$). Prepartum dietary changes affected milk composition during the first 3 wk of lactation. Milk fat content tended ($P = 0.07$) to decrease by 8.33% during the first 3-wk period in cows fed the HMP diet prepartum. Milk protein content tended ($P = 0.06$) to increase during the first 3-wk period in cows fed the HMP diet during the prepartum period. Milk fat, protein, and lactose yields were not affected during the first 3 wk of lactation ($P > 0.10$). Over the 9 wk of lactation, milk composition was not affected by prepartum dietary MP supply and feed intake ($P > 0.10$) except for an increasing trend in milk protein yield with HMP versus LMP diet ($P = 0.10$). Milk fat content and yield were increased in ALI versus CNI cows during the first 3-wk period when fed LMP versus HMP diet (MP × I interaction, $P \leq 0.05$). As lactation progressed, milk yield increased, milk fat and protein contents and milk fat yield decreased, and milk lactose content and yield increased in all treatments over the 9 wk of lactation (T, $P < 0.01$).

BCS and BW

Treatment means for BCS, BW, and changes in BCS and BW during the pre- and postpartum periods are presented in Table 5. Prepartum and postpartum BCS and BW were similar among different treatment groups ($P > 0.10$). However, pre- and postpartum changes in BW and BCS were affected by prepartum dietary intake ($P < 0.05$). Regardless of MP level ($P > 0.10$), cows in ALI group gained more BW and BCS prepartum and lost more BW and BCS postpartum than cows in CNI group ($P < 0.05$). All cows gained BW and BCS as calving approached and lost BW and BCS as lactation progressed (T, $P < 0.01$). The MP × I interaction for BCS change ($P < 0.01$) and a MP × I × T interaction for BCS ($P = 0.01$) indicated that postpartum loss of BW and BCS in ALI cows compared with CNI cows was greater in cows fed LMP diet than those fed HMP diet.

Serum Metabolites

Effects of prepartum dietary treatments on serum metabolites are presented in Table 6. Prepartum serum BUN concentration increased by 37.6% in the cows fed HMP diet ($P < 0.01$). Prepartum serum glucose, FFA, BHB, TG, and cholesterol did not differ among treatment groups ($P > 0.10$). After calving, serum BHB ($P = 0.02$) decreased and FFA tended to decrease ($P = 0.08$) by 24.3 and 29.3%, respectively, during the first 3-wk period in cows fed HMP diet. An interaction of MP × I observed on serum FFA concentration over the 9 wk of lactation indicated that serum FFA increased in ALI cows compared with CNI cows fed LMP diet, whereas no change was observed in ALI cows fed HMP diet ($P = 0.03$). The concentrations of glucose, BUN, TG, and cholesterol were not affected by prepartum dietary MP level ($P > 0.10$). Serum BHB concentration increased by 28.4% in ALI cows compared with CNI cows over the 9 wk of lactation ($P < 0.01$). There was a MP × I × T interaction on serum BHB concentration indicating that increase in serum BHB in ALI cows than CNI cows was greater during the first 3 wk of lactation when fed the LMP diet compared with those fed HMP diet ($P < 0.01$). Serum TG concentration increased in the ALI cows over the 9 wk of lactation compared with the CNI cows ($P = 0.04$). An increase in the concentrations of BHB and TG was observed with the LMP diet compared with the HMP diet as calving approached (MP × T interaction, $P < 0.01$). Postpartum serum BHB, FFA, and TG decreased in all cows, whereas serum glucose and cholesterol increased over the 9 wk of lactation (T, $P \leq 0.03$).

DISCUSSION

Investigating the interaction of low (65 g/kg of DM) and high prepartum dietary MP (90 g/kg of DM) fed for controlled versus ad libitum intake [100 and 160% of the NRC (2001) energy requirements, respectively] on lactation performance of multiparous dairy cows was the main focus of the current study. A prepartum energy balance of 105 versus 165% of the NRC (2001) requirements in CNI versus ALI groups, respectively, was achieved in both low and high MP groups. The effects of time relative to calving are consistent with the previous studies on DMI, milk yield and composition, BW, BCS (Dann et al., 2006; Douglas et al., 2006; Janovick and Drackley, 2010), serum metabolites (Dann et al., 2006; Douglas et al., 2006; Janovick et al., 2011), and feeding behavior (Proudfoot et al., 2009; Mullins et al., 2012; Yuan et al., 2015). In our study, prepartum

Table 4. Effects of prepartum intake and dietary MP level on milk production and composition

Item	Close-up period treatment[1]					P-value[2]							
	HMP		LMP										
	ALI	CNI	ALI	CNI	SEM	MP	I	T	MP × I	MP × T	I × T	MP × I × T
Wk 1–3												
Actual milk, kg/d	20.6	22.5	20.9	17.3	1.89	0.16	0.61	<0.01	0.12	0.67	0.30	0.56
ECM,[3] kg/d	21.2	25.2	24.4	18.8	2.29	0.44	0.69	<0.01	0.02	0.58	0.87	0.88
3.4% PCM,[4] kg/d	17.9	20.2	18.5	15.2	1.79	0.17	0.76	<0.01	0.09	0.31	0.74	0.69
Fat, %	4.00	4.47	4.80	4.44	0.227	0.07	0.80	0.17	0.05	0.15	0.46	0.64
Fat, g/d	822	998	1,001	769	68.5	0.69	0.66	<0.01	<0.01	0.20	0.90	0.20
Protein, %	2.96	3.08	2.96	2.91	0.052	0.06	0.49	<0.01	0.07	0.26	0.27	0.06
Protein, g/d	608	686	617	510	62.5	0.15	0.80	<0.01	0.11	0.53	0.74	0.82
Lactose, %	4.48	4.55	4.45	4.40	0.064	0.11	0.80	<0.01	0.29	0.76	0.68	0.11
Lactose, g/d	922	1,019	926	770	96.3	0.17	0.74	<0.01	0.16	0.21	0.57	0.83
Wk 1–9												
Actual milk, kg/d	23.6	26.5	22.7	20.8	1.81	0.05	0.78	<0.01	0.14	0.32	0.59	0.57
ECM,[3] kg/d	23.5	26.1	23.4	20.2	1.74	0.06	0.81	<0.01	0.07	0.80	0.58	0.05
3.4% PCM,[4] kg/d	19.6	22.6	19.2	18.4	1.50	0.09	0.42	<0.01	0.16	0.33	0.33	0.42
Fat, %	3.80	3.67	3.90	3.97	0.170	0.20	0.86	<0.01	0.51	0.42	0.11	0.06
Fat, g/d	891	972	880	825	60.1	0.15	0.80	<0.01	0.22	0.38	0.60	0.11
Protein, %	2.84	2.90	2.84	2.89	0.041	0.73	0.11	<0.01	0.83	0.07	0.20	0.13
Protein, g/d	666	766	647	613	55.5	0.10	0.52	<0.01	0.19	0.59	0.17	0.39
Lactose, %	4.27	4.33	4.25	4.36	0.058	0.96	0.11	<0.01	0.64	0.44	0.26	0.21
Lactose, g/d	1,004	1,144	975	920	83.4	0.11	0.57	<0.01	0.21	0.40	0.14	0.35
63-d cumulative milk yield, kg	1,488	1,672	1,436	1,310	109.9	0.04	0.77	—	0.13	—	—	—

[1]LMP = 65 g/kg MP of DM and HMP = 90 g/kg MP of DM offered for ad libitum intake (ALI) to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation and controlled intake (CNI) to restrict NE_L intake to 100% of the NRC (2001) recommendation from −21 d relative to expected parturition until parturition.

[2]Probability of treatment effects: MP = effects of prepartum dietary MP level, HMP versus LMP diets; I = effects of prepartum feed intake, ALI versus CNI; T = effects of time as weeks relative to calving.

[3]ECM = [0.327 × milk (kg)] + [12.95 × fat (kg)] + [7.65 × true protein (kg)] following Tyrrell and Reid (1965).

[4]Protein-corrected milk = milk (kg/d) × 0.294% CP (Charbonneau et al., 2006).

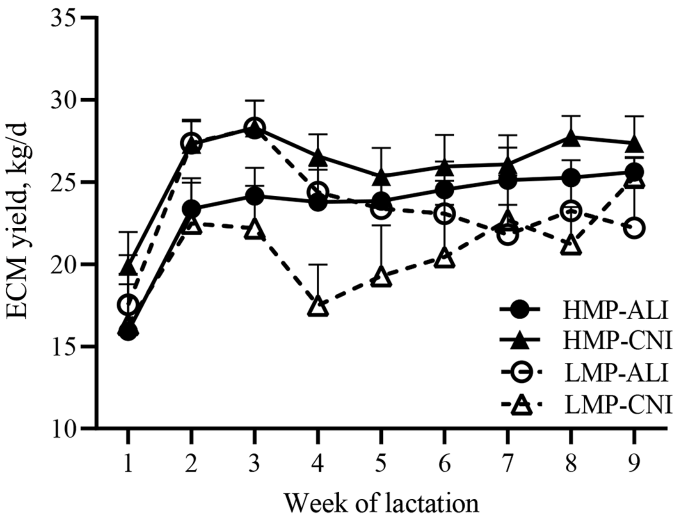

Figure 1. Least squares means for ECM yield (kg/d) of dairy cows fed different diets during the prepartum period. Prepartum diet: HMP-ALI = cows fed high MP (90 g/kg of DM) diet for ad libitum intake to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation for NE_L; HMP-CNI = cows fed high MP (90 g/kg of DM) diet for controlled intake to control NE_L intake to ~100% of the NRC (2001) recommendation for NE_L; LMP-ALI = cows fed low MP (65 g/kg of DM) diet for ad libitum intake to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation for NE_L; LMP-CNI = cows fed low MP (65 g/kg of DM) diet for controlled intake to control NE_L intake to ~100% of the NRC (2001) recommendation for NE_L. Cows were fed diets from 21 d before expected parturition through parturition. All cows were fed a similar lactation diet.

average eating time of 255 min/d in ALI cows with 13.9 kg/d of DMI was close to the previously reported total eating time of 259 min/d with 14.5 kg/d of DMI (Zimpel et al., 2018). The postpartum average daily eating time of all the cows: 291 min/d in our study was also similar to the total eating time of 294 min/d with 11.9 meals/d in tiestall system observed during early lactation (Dado and Allen, 1995).

HMP Diet During the Prepartum Period Increased Postpartum DMI

In this study, an increase in the postpartum DMI during the first 3 wk and an increasing trend over the 9 wk with HMP diet was observed in agreement with Amirabadi Farahani et al. (2017). Moreover, the increased DMI was accompanied by a high meal frequency with HMP diet in accordance with earlier reports (Huzzey et al., 2005; Zimpel et al., 2018). The low BHB and FFA with HMP diet could explain the increase in DMI as the DMI is also controlled by fatty acid oxidation during the periparturient period (Allen et al., 2009; Allen and Piantoni, 2013). Interestingly, increased hepatic oxidation of fatty acids is reported to increase discomfort, decrease appetite, and inhibit

Table 5. Effects of prepartum intake and dietary MP level on BW and BCS

Item	Close-up period treatment[1]					*P*-value[2]						
	HMP		LMP									
	ALI	CNI	ALI	CNI	SEM	MP	I	T	MP × I	MP × T	I × T	MP × I × T
Prepartum												
BCS[3]	3.34	3.39	3.26	3.41	0.064	0.67	0.12	<0.01	0.39	1.00	0.70	1.00
BW, kg	623	630	614	645	23.1	0.90	0.40	<0.01	0.58	0.40	<0.01	0.22
BCS change[4]	0.14	0.06	0.19	−0.05	0.067	0.68	0.02	—	0.22			
BW change,[4] kg	27.4	2.63	43.1	−8.89	10.11	0.83	<0.01	—	0.17			
Postpartum												
BCS	2.90	2.87	2.74	2.93	0.078	0.48	0.31	<0.01	0.17	0.37	<0.01	0.01
BW, kg	555	545	542	554	19.4	0.93	0.96	<0.01	0.54	0.81	0.03	0.23
BCS change[5]	−0.41	−0.36	−0.63	−0.14	0.082	0.94	<0.01	—	<0.01			
BW change,[5] kg	−30.5	−20.9	−54.2	2.83	16.13	0.99	0.02	—	0.10			

[1]LMP = 65 g/kg MP of DM and HMP = 90 g/kg MP of DM offered for ad libitum intake (ALI) to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation and controlled intake (CNI) to restrict NE_L intake to 100% of the NRC (2001) recommendation from −21 d relative to expected parturition until parturition.

[2]Probability of treatment effects: MP = effects of prepartum dietary MP level, HMP versus LMP diets; I = effects of prepartum feed intake, ALI versus CNI; T = effects of time as weeks relative to calving.

[3]Body condition score was assigned using a 5-point scale with increments of 0.25, following Edmonson et al. (1989).

[4]Prepartum changes for both BCS and BW were calculated from wk −3 to wk −1 relative to parturition.

[5]Postpartum changes for both BCS and BW were calculated from wk 1 through wk 9 relative to parturition.

Table 6. Effects of prepartum intake and dietary MP level on blood metabolites

Item	Close-up period treatment[1]					P-value[2]						
	HMP		LMP									
	ALI	CNI	ALI	CNI	SEM	MP	I	T	MP × I	MP × T	I × T	MP × I × T
Prepartum												
BHB, mmol/L	0.37	0.38	0.40	0.39	0.021	0.42	0.92	0.46	0.63	<0.01	0.20	0.29
FFA,[3] mEq/L	0.14	0.19	0.21	0.13	0.040	0.98	0.74	0.01	0.08	0.74	0.26	0.13
TG,[4] mg/dL	19.9	19.9	18.2	20.1	0.89	0.39	0.29	<0.01	0.27	0.02	0.30	0.83
Glucose, mg/dL	73.3	72.7	70.6	73.5	1.35	0.47	0.41	0.52	0.20	0.52	0.08	0.57
Cholesterol, mg/dL	88.2	89.9	101	101	8.03	0.13	0.91	<0.01	0.92	0.94	0.07	0.31
BUN, mg/dL	15.8	16.4	11.8	10.5	1.17	<0.01	0.76	0.33	0.43	0.29	0.83	0.90
Postpartum												
Wk 1–3												
BHB, mmol/L	0.46	0.41	0.70	0.45	0.054	0.02	0.01	0.01	0.06	0.63	<0.01	0.02
FFA, mEq/L	0.19	0.22	0.38	0.20	0.044	0.08	0.07	0.03	0.02	0.43	0.64	0.23
TG, mg/dL	17.8	17.6	18.2	17.6	0.36	0.68	0.36	0.54	0.58	0.15	0.76	0.36
Glucose, mg/dL	64.9	62.3	63.0	67.7	2.37	0.45	0.65	0.03	0.13	0.47	0.83	0.45
Cholesterol, mg/dL	98.7	85.1	91.6	98.1	6.39	0.64	0.57	<0.01	0.11	0.40	0.64	0.12
BUN, mg/dL	14.7	16.0	14.9	14.7	0.96	0.55	0.54	0.46	0.43	0.77	0.62	0.57
Wk 1–9												
BHB, mmol/L	0.51	0.42	0.62	0.46	0.039	0.06	<0.01	0.01	0.33	0.01	<0.01	<0.01
FFA, mEq/L	0.19	0.22	0.32	0.21	0.031	0.08	0.17	0.11	0.03	0.37	0.40	0.26
TG, mg/dL	17.6	17.3	18.0	17.1	0.25	0.72	0.04	0.03	0.27	0.34	0.29	0.10
Glucose, mg/dL	65.6	63.7	65.6	69.8	2.09	0.14	0.56	<0.01	0.14	0.41	0.65	0.31
Cholesterol, mg/dL	133	123	122	138	9.3	0.81	0.74	<0.01	0.14	0.93	0.48	0.67
BUN, mg/dL	15.1	16.3	14.9	14.6	0.81	0.25	0.55	0.50	0.34	0.76	0.59	0.60

[1]LMP = 65 g/kg MP of DM and HMP = 90 g/kg MP of DM offered for ad libitum intake (ALI) to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation and controlled intake (CNI) to restrict NE_L intake to 100% of the NRC (2001) recommendation from −21 d relative to expected parturition until parturition.

[2]Probability of treatment effects: MP = effects of prepartum dietary MP level, HMP versus LMP diets; I = effects of prepartum feed intake, ALI versus CNI; T = effects of time as weeks relative to calving.

[3]FFA = free fatty acids.

[4]TG = triglycerides.

the feeding behavior of dairy cows (Allen et al., 2009; van Hoeij et al., 2019). In the present experiment, a negative effect on postpartum meal frequency and meal length in LMP-ALI cows could possibly be a result of increased serum BHB concentration.

In contrast to our findings, some studies reported either no change (Huyler et al., 1999; Park et al., 2002) or a decrease (Greenfield et al., 2000; Hartwell et al., 2000) in the postpartum DMI with increased prepartum dietary protein supplies. These inconsistent responses in the literature could be related to the variable MP density of experimental diets, because an increase in the postpartum DMI was observed only when dietary MP density was <90 g/kg during the prepartum period (Park et al., 2002; Amirabadi Farahani et al., 2019) and ≤109 g of MP/kg of DM during the postpartum phase (Dale et al., 2017; Amirabadi Farahani et al., 2017). Both conditions were met in our study as MP density was 65 to 90 g/kg during the prepartum period and 83.3 g/kg during the postpartum phase.

Similar Postpartum DMI Between Controlled Versus Ad Libitum Intake

In our study, the postpartum DMI of CNI cows was similar to ALI cows in agreement with previous reports where energy levels were increased from 80% to 150% of the requirements (Dann et al., 2005; Dann et al., 2006; Janovick and Drackley, 2010). Moreover, compared with the prepartum period, the increase in the postpartum DMI was 125 ± 15% in the CNI versus 48 ± 9.4% in the ALI cows during the first 3 wk of lactation, indicating a relatively high recovery of DMI by the controlled feeding strategy. This finding was in agreement with the literature studies where the recovery of the DMI represented 171 ± 31% in the restricted versus 63 ± 18% in the ad libitum cows during pre- to postpartum period (Dann et al., 2006; Douglas et al., 2006, 2007). Moreover, this increase in the DMI could only be associated with the physical restriction of energy, as the studies where prepartum dietary energy was controlled through density and diets were fed ad libitum showed an increase in the DMI by 33 ± 14% in the low energy versus 37 ± 4.0% in the high energy treatment from pre- to postpartum phase (Vandehaar et al., 1999; Doepel et al., 2002). Interestingly, the CNI cows increased their eating rate by 89% during the first 3 wk of the postpartum period compared with the prepartum period, whereas this increase was only 43% in ALI cows. Accordingly, it could be inferred that adjusting to a higher eating rate allowed the CNI cows to consume the same DMI as the ALI cows, as has been reported previously (Dann et al., 2005; Douglas et al., 2006, 2007). Such behavioral adjustments were further supported by low BHB in CNI cows over the 9-wk postpartum period.

Milk Yield Increased in Cows Fed HMP Diet

The milk production with HMP diet increased parallel to the DMI over the 9 wk of lactation in agreement with the literature (Huyler et al., 1999; Phillips et al., 2003; Amirabadi Farahani et al., 2017). However, increased DMI accounts for only about half of the milk yield response to selection (Patton et al., 2007). Other factors explaining the increased milk yield with HMP diet could be a possible reduction in prepartum protein mobilization (Bell et al., 2000; Stockdale and Roche, 2002; Amirabadi Farahani et al., 2017) coupled with lower postpartum concentrations of BHB and FFA (Carlson et al., 2006). The increasing trend in milk protein yield over the 9-wk period with the HMP diet further supports the literature showing adequate MP supply during the prepartum period could increase the postpartum AA availability for milk protein synthesis (Bell et al., 2000; Larsen and Kristensen, 2013; Kokkonen, 2014). However, the effects of the prepartum dietary MP supply mostly appear during first 3 to 4 wk of lactation (Bell et al., 2000; Dalbach et al., 2011). Decreased BHB and FFA in CNI cows coupled with an increased intake of HMP cows resulted in increased ECM in HMP-CNI cows. On the other hand, lowest milk yield and ECM were observed in LMP-CNI cows as the prepartum MP supplies (593 g/d) were too low to support milk production, despite having less BHB compared with LMP-ALI cows, leading to a MP × I interaction on ECM. These findings were in agreement with Dewhurst et al. (2000) where a prepartum diet with the lowest MP (528 g/d) and energy intake (10.8 Mcal/d) produced the lowest milk during the first 4 wk of lactation. In our study, the actual milk and ECM yields were not different between the ALI and CNI groups, in agreement with previous studies when prepartum energy was controlled to provide 80 and 150% (Dann et al., 2006), 100 and 150% (Graugnard et al., 2013), or 100, 125, and 150% (Mann et al., 2015) of the NRC (2001) requirements.

Highest BCS Loss and Milk Fat in LMP-ALI Cows

Although a certain degree of loss in BCS during the postpartum period seems to be unavoidable, the magnitude of loss in BCS was different among the treatment groups. Not surprisingly, loss in the BCS and BW was more pronounced in the ALI cows. Interestingly, the presence of the MP × I × T interaction on BCS showed that LMP-ALI cows continued to lose and LMP-CNI cows started to regain BCS during the postpartum pe-

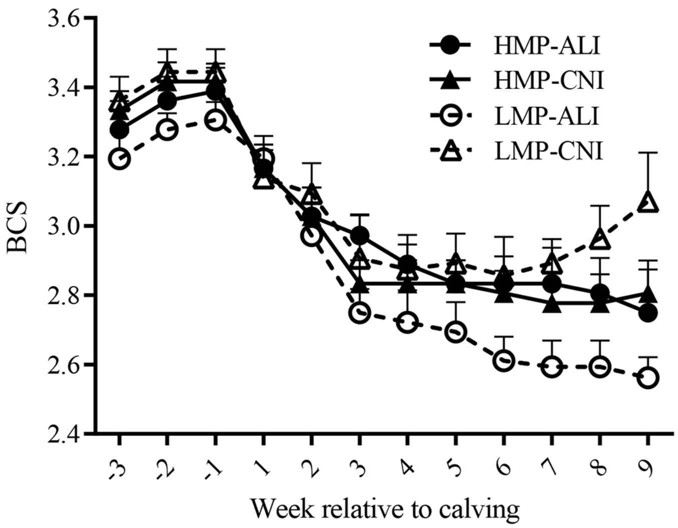

Figure 2. Least squares means for BCS of dairy cows fed different diets during the prepartum period. Prepartum diet: HMP-ALI = cows fed high MP (90 g/kg of DM) diet for ad libitum intake to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation for NE_L; HMP-CNI = cows fed high MP (90 g/kg of DM) diet for controlled intake to control NE_L intake to ~100% of the NRC (2001) recommendation for NE_L; LMP-ALI = cows fed low MP (65 g/kg of DM) diet for ad libitum intake to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation for NE_L; LMP-CNI = cows fed low MP (65 g/kg of DM) diet for controlled intake to control NE_L intake to ~100% of the NRC (2001) recommendation for NE_L. Cows were fed diets from 21 d before expected parturition through parturition. All cows were fed a similar lactation diet.

riod. The interaction also showed that cows fed HMP-ALI had a higher BCS loss than those fed HMP-CNI during the prepartum period; however, the difference was not as great as with the LMP diet (Figure 2). The MP × I × T interaction for BHB was observed mainly because of a higher BHB level in LMP-ALI cows during the first 3 wk of lactation compared with other treatments (Figure 3). The MP × I interaction for milk fat content, BCS loss, and FFA also indicated the highest fat mobilization in LMP-ALI cows during the first 3 wk of lactation in our study. The literature shows that during the immediate postpartum period, approximately 50% of FFA are either oxidized or incorporated into milk fat (Bell, 1995). Feeding a high energy diet during the prepartum period could increase milk fat showing high fat mobilization (Keady et al., 2005). In our study, a low MP:NE_L ratio of the LMP diet might also have exacerbated the mobilization of body fat in LMP-ALI cows due to prepartum high fat and less protein deposition.

MP Requirement During the Close-Up Period

Previous reviews of the literature (Bell et al., 2000; Stockdale and Roche, 2002) and meta-analyses (Kokkonen, 2014; Husnain and Santos, 2019) highlighted the inconsistencies in the response of postpartum DMI, milk yield, and milk composition to increasing the prepartum dietary MP supply. In our study, the HMP-ALI and HMP-CNI supplied 475 and 164 g/d more MP, respectively, compared with the requirements estimated by the NRC (2001) model. An increase in milk production and a decrease in postpartum serum FFA and BHB concentrations with the HMP diet indicate the direct positive response of cows to this additional prepartum MP supply of the NRC (2001) requirements. Moreover, discernible benefits of prepartum controlled intake were observed as the HMP-CNI cows produced more ECM and had less serum BHB despite consuming 79 g/d less MP than LMP-ALI cows. In our study, an increase in the postpartum BCS loss and increased serum FFA and BHB with the ad libitum intake [160% of the NRC (2001) requirements] were more evident with the low MP diet (65 g/kg of DM) indicating that diet should be composed of high MP density (90 g/kg of DM) to minimize the metabolic stress in transition cows when controlled intake [100% of the NRC (2001) requirements] is not feasible.

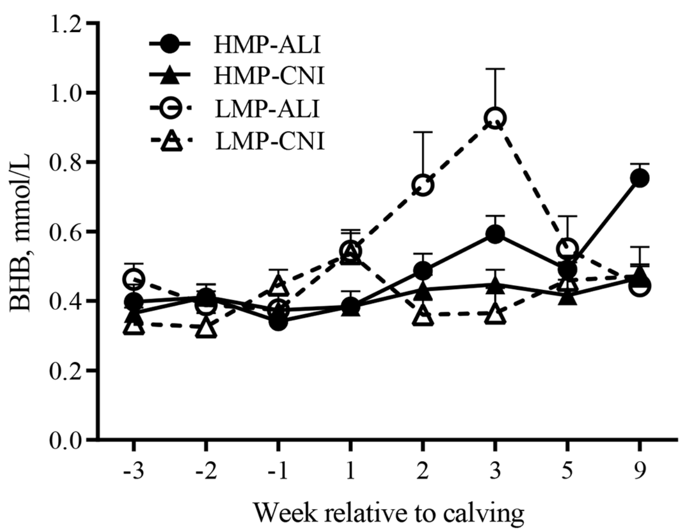

Figure 3. Least squares means for BHB (mmol/L) of dairy cows fed different diets during the prepartum period. Prepartum diet: HMP-ALI = cows fed high MP (90 g/kg of DM) diet for ad libitum intake to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation for NE_L; HMP-CNI = cows fed high MP (90 g/kg of DM) diet for controlled intake to control NE_L intake to ~100% of the NRC (2001) recommendation for NE_L; LMP-ALI = cows fed low MP (65 g/kg of DM) diet for ad libitum intake to achieve NE_L intake in excess (~160%) of the NRC (2001) recommendation for NE_L; LMP-CNI = cows fed low MP (65 g/kg of DM) diet for controlled intake to control NE_L intake to ~100% of the NRC (2001) recommendation for NE_L. Cows were fed diets from 21 d before expected parturition through parturition. All cows were fed a similar lactation diet.

CONCLUSIONS

The high MP concentration diet fed during the prepartum period increased the postpartum DMI, milk yield, and improved metabolic status by lowering the BHB levels. There was no difference in the DMI and milk production when the prepartum diets were offered ad libitum or restricted. Similar eating rate during the postpartum phase in all treatments and higher increase in the eating rate from pre- to postpartum phase between restricted versus ad libitum cows showed a higher recovery of the DMI in restricted cows during the postpartum phase. Presence of several interactions between MP concentration and feed intake showed that feeding of high protein diet with controlled intake appears to be a promising nutritional approach for multiparous transition cows in term of performance and health. On the other hand, cows fed the ad libitum low MP diet performed better compared with the restricted cows with greater BCS loss and BHB levels.

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