Effect of concentrate feeding method on the performance of dairy cows in early to mid lactation

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ABSTRACT

The objective of the current study was to determine the effects of concentrate feeding method on milk yield and composition, dry matter (DM) intake (DMI), body weight and body condition score, reproductive performance, energy balance, and blood metabolites of housed (i.e., accommodated indoors) dairy cows in early to mid lactation. Eighty-eight multiparous Holstein-Friesian cows were managed on 1 of 4 concentrate feeding methods (CFM; 22 cows per CFM) for the first 21 wk postpartum. Cows on all 4 CFM were offered grass silage plus maize silage (in a 70:30 ratio on a DM basis) *ad libitum* throughout the study. In addition, cows had a target concentrate allocation of 11 kg/cow per day (from d 13 postpartum) via 1 of 4 CFM, consisting of (1) offered on a flat-rate basis via an out-of-parlor feeding system, (2) offered based on individual cow's milk yields in early lactation via an out-of-parlor feeding system, (3) offered as part of a partial mixed ration (target intake of 5 kg/cow per day) with additional concentrate offered based on individual cow's milk yields in early lactation via an out-of-parlor feeding system, and (4) offered as part of a partial mixed ration containing a fixed quantity of concentrate for each cow in the group. In addition, all cows were offered 1 kg/cow per day of concentrate pellets via an in-parlor feeding system. We detected no effect of CFM on concentrate or total DMI, mean daily milk yield, concentrations and yields of milk fat and protein, or metabolizable energy intakes, requirements, or balances throughout the study. We also found no effects of CFM on mean or final body weight, mean or final body condition score, conception rates to first service, or any of the blood metabolites examined. The results of this study suggest that CFM has little ef-

fect on the overall performance of higher-yielding dairy cows in early to mid lactation when offered diets based on conserved forages.

Key words: concentrate feeding method, total mixed ration, feed-to-yield, flat-rate, confinement

INTRODUCTION

The adoption of breeding programs with considerable emphasis on milk production has increased the milk yields of Holstein-Friesian dairy cattle populations in many countries in recent years (see review by Oltenacu and Broom, 2010). Increased milk yields are normally accompanied by an increase in feed intake potential and the increased ability of these higher-yielding cows to mobilize body tissue to provide energy for milk production in early lactation (Ferris et al., 1999). Body tissue mobilization indicates that a cow is in negative energy balance, with the adverse effects of negative energy balance on reproductive performance (Domecq et al., 1997; Berry et al., 2003; Buckley et al., 2003) and cow health (Collard et al., 2000) now well documented. In an attempt to minimize the extent of negative energy balance experienced and to allow higher-yielding cows to achieve their potential milk yields, the quantity of concentrates offered to these cows has increased. Due to the large quantities of concentrates offered to cows in many production systems, the concentrate feeding method adopted may affect cow performance.

A wide range of concentrate feeding methods is adopted in practice, both in the United Kingdom and in many other parts of the world. For example, concentrates can be mixed with the forage component of the diet as part of a mixed ration, offered separately from forage via in-parlor or out-of-parlor concentrate feeding systems, or offered via a combination of these approaches. When offered separately from forage, concentrate can be offered via several strategies, such as at a flat rate, which does not account for differences in the milk yields of individual cows, or on a feed-to-yield

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basis, where individual cows are offered specific concentrate allocations based on their actual milk yields. The latter strategy has been facilitated by developments in concentrate feeding technology, which allow feeding systems to be directly linked to milking parlor software, thereby allowing cows to be offered concentrates based on their individual milk yields.

Several studies have examined the effects of offering concentrate as part of a total mixed ration versus separately from silage on dairy cow performance. In a study involving lower-yielding cows (range of mean milk yields of approximately 18 to 22 kg/cow per day) with low concentrate DMI (1.8 to 7.0 kg/cow per day), Agnew et al. (1996) found no difference in milk yields between the 2 systems. Gordon et al. (1995) and Yan et al. (1998) reported similar findings for higher-yielding cows (29 to 35 kg/cow per day) at a higher concentrate DMI (10.9 to 12.9 kg/cow per day).

In addition, several authors have examined the effect of concentrate allocation strategy, in which cows are offered concentrates separately from silage at a flat rate or on a feed-to-yield basis (where both groups received the same total amount of concentrates) and reported no difference in milk yields between these strategies (Gordon, 1982; Taylor and Leaver, 1984a,b). However, these studies involved low- or moderate-yielding cows (range of mean treatment milk yields across these studies of 22 to 26 kg/cow per day) and relatively low concentrate DMI (7.5 to 7.8 kg/cow per day). In addition, within the feed-to-yield treatments examined in the 3 latter studies, the entire concentrate components of the diets were offered via either in-parlor or out-of-parlor concentrate feeding systems. However, in many feed-to-yield systems adopted in practice, cows are offered a basal diet consisting of a forage-plus-concentrate mix, which is generally designed to provide a cow's maintenance energy requirement plus the energy required for the production of a specific milk yield. Additional concentrates are then offered to support milk yields above those sustained by the basal diet. This approach was adopted by Lawrence et al. (2015), who found no difference in the performance of cows offered concentrates at a flat rate or on a feed-to-yield basis. However, that study involved relatively low-yielding cows (23 to 25 kg of milk/cow per day) with low concentrate DMI (3.9 to 7.0 kg/cow per day).

We are unaware of studies that have examined the effects of concentrate feeding method, consisting of different concentrate feeding systems (i.e., mixed with the forage versus separate from forage) and concentrate allocation strategies (flat rate versus feed-to-yield), on the performance of high-yielding dairy cows (i.e., those with milk yields of approximately 40 kg/cow per day) when housed and offered conserved forage based diets.

Given the differences in the physical presentation of the diets and in how concentrates are allocated to individual cows with the approaches described above, it is possible that cow performance would be affected by concentrate feeding system. Thus, the objective of this study was to examine the effects of concentrate feeding method on milk production and composition, BW and BCS, reproductive performance, energy balance, and blood metabolites of higher-yielding dairy cows in early to mid lactation.

MATERIALS AND METHODS

This study was conducted at the Agri-Food and Biosciences Institute (**AFBI**), Hillsborough, Northern Ireland. All experimental procedures were conducted under an experimental license granted by the Department of Health, Social Services & Public Safety for Northern Ireland in accordance with the Animals (Scientific Procedures) Act 1986.

Prepartum Housing and Management

For 3 wk before their expected calving date, 88 multiparous Holstein-Friesian dairy cows [mean (SD) lactation number of 3.4 (1.36); mean PTA for milk fat-plus-protein yield of 15.1 (13.2) kg; mean Profitable Lifetime Index of £162 (£148.1): December 2014 proof run] were housed and given ad libitum access (1.07 of the previous day's intake) to a grass silage-based diet. Cows had a mean calving date of October 16, 2011, with all cows calving between August 29, 2011, and January 5, 2012.

During the 3-wk prepartum period, cows were housed as a single group in a freestall house with concrete flooring and had access to individual cubicles that were fitted with rubber mats and bedded with sawdust. The cubicle-to-cow ratio was $\geq 1:1$ at all times, thus meeting the recommendations of FAWC (1997). The floor area was scraped every 3 h using an automated system. During this time, cows were given ad libitum access to grass silage supplemented with precalving minerals and calcined magnesite, with the latter being mixed in the silage to achieve target intakes of 150 and 30 g/cow per day, respectively.

Concentrate Feeding Methods

Following parturition, cows were allocated to 1 of 4 concentrate feeding methods (**CFM**; 22 cows per treatment), with these CFM comprising different concentrate feeding systems and allocation strategies. Cows on each CFM were balanced for 305-d milk yield during the previous lactation; parity; PTA for milk fat,

protein, and fat-plus-protein yields; Profitable Lifetime Index; and BW and BCS at 3 wk prepartum. Cows remained on the experimental treatments until they reached 21 wk postpartum, during which time all cows were housed (as previously described for prepartum management).

The forage component of the diet offered with each CFM comprised a mixture of grass silage and maize silage (in a 70:30 ratio on a DM basis), with these forages mixed for approximately 5 min in a complete-diet mixer wagon (Redrock, Armagh, UK). In addition, cows were offered concentrates via 1 of 4 CFM (described below), with the objective being that total concentrate intakes during the experimental period would be similar for each treatment group. The target total concentrate intake for cows on each treatment group during the experimental period (wk 2 to 21 postpartum) was approximately 1,760 kg/cow. This target intake was deemed appropriate based on the expected milk yields of the cows on the experiment and the quality of the silages available. From d 13 postpartum, a mean daily concentrate intake of 12 kg/cow per day was targeted, with 11.0 kg of this being offered via 1 of the 4 CFM and the remaining 1.0 kg offered via an in-parlor concentrate feeding system (0.5 kg/cow at each milking). The 4 CFM were as follows:

1. Out-of-parlor feeding, flat rate (**OPF-F**): Cows were offered the forage mix (described above) ad libitum (1.07 of the previous day's intake), plus concentrates via an out-of-parlor feeding system. Concentrate allocations to each cow increased from 5.0 kg/cow per day on d 1 postpartum, in increments of 0.5 kg/cow per day until d 13 postpartum, at which point the target concentrate allocation from the out-of-parlor feeders of 11.0 kg/cow per day was achieved. Thereafter, this concentrate allocation remained unchanged (flat rate) until the end of the experiment.
2. Out-of-parlor feeding, yield based (**OPF-Y**): Cows were offered the forage mix (described above) ad libitum (1.07 of the previous day's intake), plus concentrates via an out-of-parlor feeding system. Concentrates were offered as per the OPF-F treatment until d 13 postpartum, after which concentrates were offered using a yield-based allocation strategy via an out-of-parlor feeding system. The adoption of this yield-based strategy, rather than a conventional feed-to-yield strategy was necessary to ensure that the target concentrate allocation was achieved with this treatment. The approach adopted involved cows being initially allocated to 1 of 3 concentrate allocation curves (high, medium, or low) based on

their mean daily milk yield between d 10 and 14 postpartum (>38 , 33 to 38, or <33 kg/cow per day, for the high, medium, and low curves, respectively). The concentrate allocation curves were developed to follow typical lactation curves for cows within these milk yield ranges at d 10 to 14 postpartum (based on milk yield curves derived from historical data sets at AFBI) and to achieve the target total concentrate allocations described previously. The curve to which each cow was initially assigned was reassessed based on their individual milk yields during d 18 to 21 postpartum (milk yields of >45 , 36 to 45, and <36 kg/cow per day were required for allocation to the high, medium, and low curves, respectively), and several cows were reassigned to a different curve. The quantity of concentrates offered to cows on each of these curves was adjusted weekly to preset allocations throughout the experiment. For example, during wk 4, 8, 12, 16, and 20 postpartum, cows allocated to the high curve were offered 14.5, 16.3, 14.8, 12.5, and 10.9 kg of concentrate per day, respectively, whereas cows on the medium and low curves were offered 10.8, 12.5, 11.6, 11.0, and 10.1 kg/d, and 8.2, 7.8, 7.5, 7.2, and 6.8 kg/d, respectively. Overall, cows on these curves had mean concentrate allocations of 7.5, 11.2, and 13.7 kg/cow per day from wk 2 to 21 postpartum. In total, 8, 7, and 7 cows were assigned to the high, medium, and low curves, respectively, from d 21 postpartum onward.

3. Partial mixed ration, yield-based (**PMR-Y**): Throughout the experiment, cows were offered a partial mixed ration ad libitum (at 1.07 of the previous day's intake) comprising the forage mix (described earlier) plus concentrates, with the latter included in the mix to achieve an intake of 5.0 kg/cow per day. This partial mixed ration was designed to supply the maintenance energy requirements of the cows plus the energy required to sustain milk yields of 27 kg/cow per day. In addition to the concentrate offered as part of the partial mixed ration, concentrates were offered via an out-of-parlor feeding system. Cows were offered 0.5 kg/cow per day on d 2 postpartum, with this allocation increased by 0.5 kg/cow per day until d 13 postpartum, at which point cows were offered 6.0 kg of concentrate daily via the out-of-parlor feeders. Thus, the target mean daily concentrate allocation (from the partial mixed ration and out-of-parlor feeder) of 11.0 kg/cow per day was achieved at d 13 postpartum. At this point, cows were allocated to 1 of 3 concentrate

allocation curves (high, medium, or low) based on their mean daily milk yields between d 10 and 14 postpartum (>38 , 33 to 38, or <33 kg/cow per day, for the high, medium, or low curves, respectively). As with the OPF-Y treatment, the concentrate allocation curves were developed to follow typical lactation curves for cows within these milk yield ranges at d 10 to 14 postpartum. The curve to which each cow was initially assigned was reassessed based on their individual milk yields during d 18 to 21 postpartum (milk yields of >45 , 36 to 45, and <36 kg/cow per day were required for allocation to the high, medium, and low curves, respectively), and several cows were reassigned to a different curve at this time. The quantity of concentrates offered to cows on each of these curves was adjusted weekly to pre-set allocations throughout the experiment. For example, cows allocated to the high curve were offered 7.8, 9.3, 8.9, 8.2, and 8.4 kg of concentrate per day during wk 4, 8, 12, 16, and 20 postpartum, respectively. Similarly, cows on the medium and low curves were offered 5.3, 6.6, 6.4, 5.5, and 4.7 kg/cow per day, and 3.1, 1.2, 1.2, 0.9, and 0.8 kg/cow per day, respectively. In total, 7, 8, and 7 cows were assigned to the high, medium, and low curves from d 21 postpartum onward.

4. Partial mixed ration (**PMR**): Following preparation of the forage mix described above, the

concentrate component of the diet was added to the mixer wagon, and mixing continued for approximately 5 min. This PMR was then offered *ad libitum*. The total quantity of concentrates added to the PMR was determined based on the number of days since each individual cow in the group had calved: 5.0 kg/cow on d 1 postpartum, increasing by 0.5 kg/cow per day until d 13 postpartum, after which the target concentrate allocation from the PMR was 11.0 kg/cow per day.

The concentrate mixed with the silages in the PMR and PMR-Y treatments was in the form of a meal, whereas that offered via the in-parlor and out-of-parlor feeding systems was in the form of a pellet. The ingredient composition of the concentrate offered (pellet and meal) on a fresh weight basis (g/kg) was as follows: barley (200), maize (210), maize gluten feed (80), soyhulls (150), soybean (180), rapemeal (110), rumen-protected fatty acids (15), vitamins and minerals (25), and molasses (30). The chemical composition of the concentrate is presented in Table 1.

The forage mix (OPF-F and OPF-Y) and the mixed ration (PMR-Y and PMR) were prepared daily and offered between 1000 and 1100 h. Following mixing, these feeds were transferred directly from the mixer wagon to a series of feed-boxes mounted on weigh platforms. Access to feed in these boxes was controlled by a Calan gate feeding system (American Calan, North-

Table 1. Chemical composition of the grass and maize silages (g/kg of corrected DM, unless otherwise stated, except for pH), and of the concentrates (g/kg of DM, unless otherwise stated) offered during the experiment

Item	Grass silage		Maize silage		Concentrate	
	Mean	SD	Mean	SD	Mean	SD
NDF	473	42.0	458	33.7	268	12.8
ADF	274	33.3	223	22.0	133	4.9
CP	147	13.2	77	4.0	225	4.9
Starch	—	—	321	60.4	266	10.7
Ash	80	15.2	38	12.8	77	4.1
Gross energy (MJ/kg of DM)	19.9	0.92	19.3	1.22	18.3	0.11
Oven DM (g/kg of fresh weight)	240	43.5	297	13.9	883	1.9
Volatile-corrected DM (g/kg of fresh weight)	258	40.6	309	13.7	—	—
Metabolizable energy ¹ (MJ/kg of DM)	12.1	0.28	11.5	0.43	—	—
Silage fermentation variables						
Ammonia-nitrogen (g/kg of total N)	70.8	11.32	97.9	12.24	—	—
Lactic acid	136	27.5	52	21.3	—	—
Acetic acid	21.0	8.61	26.1	10.43	—	—
Propionic acid	0.74	0.758	1.07	1.581	—	—
<i>N</i> -Butyric acid	0.43	0.709	0.23	0.578	—	—
Isovaleric acid	0.15	0.446	0.04	0.129	—	—
Ethanol	28.9	19.47	8.9	6.86	—	—
Propanol	2.05	3.127	1.94	1.488	—	—
pH	3.77	0.094	3.73	0.185	—	—

¹Analyzed using near-infrared reflectance spectroscopy (NIRS).

wood, NH) linked to an automatic cow identification system (Griffith Elder, Bury St. Edmunds, UK), which recorded the weight of feed consumed by each cow each day. Uneaten food remaining in the feed-boxes (refusals) was removed daily at approximately 0830 h.

Cow Measurements

All cows were milked twice daily (between 0600 and 0800 h and between 1500 and 1700 h) throughout the experiment using a 50-point rotary milking parlor, with milk yields being automatically recorded at each milking, and a total daily milk yield for each cow for each 24-h period was calculated. Milk samples were taken during 2 consecutive milkings each week and analyzed for fat, protein, and lactose using an infrared milk analyzer (Milkoscan model 605, Foss Electric, Warrington, UK), and a weighted concentration of each constituent was determined for the 24-h sampling period. Milk energy concentrations (MJ/kg) were determined using the equation of Tyrrell and Reid (1965), with fat, protein, and lactose expressed in grams per kilogram:

$$\begin{aligned} \text{Milk energy} = & (\text{fat} \times 0.0384) + (\text{protein} \times 0.0223) \\ & + (\text{lactose} \times 0.0199) - 0.108. \end{aligned}$$

Body weight was recorded twice daily (immediately after each milking) using an automated weighbridge, and a mean weekly BW for each cow was determined. The BCS of each cow was estimated every 2 wk according to Edmondson et al. (1989) by a trained technician. Milk samples for progesterone analysis were collected 3 times per week throughout the experiment, and a preservative tablet was added to each sample (Lactab Mark III, Thompson and Cooper Ltd., Runcorn, UK). Samples were then stored at 4°C until analysis (within 4 wk). Progesterone concentrations were determined using an ELISA kit (Ridgeway Science Ltd., Lydney, UK) based on the method of Sauer et al. (1986), with the day of onset of luteal activity defined as the first day of at least 2 consecutive daily milk progesterone concentrations ≥ 3 ng/mL. Pregnancy was confirmed using an ultrasound scan carried out by a veterinarian. A total of 19, 20, 21, and 18 cows in OPF-F, OPF-Y, PMR-Y, and PMR, respectively, were included in the breeding program, with the remaining cows on each treatment designated as “do not breed.” Cows were bred using AI, with breeding commencing on December 1, 2011. No cow was bred before d 42 postpartum.

The mean daily ME requirements and ME balances (MEb) for each cow were calculated using the equations of Thomas (2004), where daily MEb (MJ/cow per day) was determined using the equation

$$\text{MEb} = \left[\left(M_{ml} \times L W^{0.75} \right) + \left(\frac{0.0013 \times L W}{K_m} \right) - 10 \right] - \text{MEi},$$

where M_{ml} is the ME required for maintenance and milk production (MJ/kg of metabolic BW), $BW^{0.75}$ is metabolic BW, K_m is the efficiency of energy use for maintenance (calculated as $0.35 \times \text{ME/gross energy} + 0.503$), and MEi is ME intake (MJ/cow per day).

Blood samples were collected before feeding from the coccygeal vein of each cow on wk 1, 3, 5, 7, 9, 11, and 13 (± 3 d) postpartum, after which they were centrifuged ($1,810 \times g$ for 15 min) to isolate the serum or plasma. Serum BHB concentrations were determined according to McMurray et al. (1984), and plasma glucose concentrations were determined using the hexokinase method (Roche Diagnostics Ltd., Burgess Hill, UK). The serum concentrations of total protein were analyzed using Boehringer Mannheim kits, and serum nonesterified fatty acid concentrations were determined using WaKo (Wako Chemicals GmbH, Neuss, Germany) kits. Serum urea concentrations were analyzed using the Kinetic UV method (Roche Diagnostics Ltd.). All analyses were undertaken using an Olympus AU640 analyzer (Olympus, Center Valley, PA).

Feed Analysis

Samples of the grass silage and maize silage offered were taken daily throughout the experiment, dried at 85°C for 18 h to determine oven DM content, and milled through a sieve with 0.8-mm apertures. Subsamples of the dried milled silages were taken twice weekly and composited every 28 d, with the composited sample analyzed for NDF, ADF, and ash concentrations. In addition, the maize silage was sampled every 14 d, dried at 60°C for 48 h, milled through a sieve with 0.5-mm aperture, and analyzed for starch concentration. A sample of the concentrate offered (pellets) was taken once every 14 d, dried at 100°C for 24 h before milling through a 0.8-mm sieve, composited every 28 d, and analyzed for CP ($N \times 6.25$), NDF, ADF, ash, and gross energy concentrations. An additional concentrate sample was taken at the same frequency, dried at 60°C for 48 h, and milled (0.5-mm sieve) before analysis for starch concentration. Concentrations of NDF and ADF were determined using a Fibertec analyzer (Fibertec FT122, Foss, Hillerød, Denmark) based on the method of Van Soest (1976), and ash concentrations were determined following combustion in a muffle furnace at 550°C for approximately 10 h. Starch concentrations were determined using a Megazyme kit (Megazyme International, Bray, Ireland). Fresh samples of the grass silage and maize silage were taken weekly and analyzed for con-

centrations of CP ($N \times 6.25$), ammonia-N, fermentation acids (lactic, acetic, propionic, *n*-butyric, and isovaleric acids), ethanol, propanol, and gross energy, and for pH. In addition, these fresh weekly silage samples were analyzed by near-infrared reflectance spectroscopy for ME concentration according to Park et al. (1998). Silage fermentation acids, ethanol, and propanol were determined using single-column GLC (Varian Star 3400 CX GC, equipped with a flame-ionization detector, Varian Inc., Palo Alto, CA), where samples were injected on-column. The CP concentrations were determined using the Kjeldahl method (Tecator Kjeltac Auto 2400/2460 Analyzer/Sampler System, Foss). Gross energy concentrations of the fresh silage and dried concentrate feeds were determined using a bomb calorimeter (Parr 6300 Bomb Calorimeter, Parr Instrument Co., Moline, IL).

Statistical Analysis

Two cows (both in the PMR treatment group) were removed from the study for reasons not associated with the treatments imposed, and their data were excluded from the statistical analysis. Data for DMI, milk yield, milk composition, ME variables, BW, BCS, days to onset of luteal activity, and days to first observed heat were analyzed using ANOVA, with each individual cow treated as the independent experimental unit. Where significant in the model, appropriate pre-experimental variables were included as covariates in the model when analyzing corresponding dependent variables [previous lactation (305 d) milk yields for milk fat, protein, fat-plus-protein, and mean daily milk yields; pre-experimental BW (3 wk prepartum) for mean BW; pre-experimental BCS (3 wk prepartum) for mean and final BCS; pre-experimental BW for forage, concentrate, and total DMI]. For variables where significant treatment effects were identified ($P < 0.05$), differences between the individual CFM were tested using Fisher's protected-adjusted multiple comparisons. Data for blood variables were analyzed using REML analysis, with week postpartum (wk 1, 3, 5, 7, 9, 11, and 13 postpartum) included as the repeated measure and as a fixed factor in the model. Weekly data for mean daily milk yields, mean daily forage DMI, and mean daily MEb throughout the experiment were analyzed using REML analysis, where week postpartum was included as the repeated measure and as a fixed factor in the model. The same covariates as used for the one-way ANOVA were included as covariates in the repeated-measures analysis. Correlations of total and silage DMI with mean daily milk yields of individual cows within each treatment, and between MEb and mean daily milk yields of cows, were analyzed using simple linear regression analysis. Data on conception rate to first

service were analyzed as a binomial distribution within a generalized linear model, where the probability value generated was a chi-probability. All data were analyzed using GenStat (16th ed., Lawes Agricultural Trust, Rothamsted, UK).

RESULTS

The chemical composition of the grass silage, maize silage, and concentrates offered are presented in Table 1. The mean (SD) CP concentrations of the grass, maize, and concentrate feeds were 147 (13.2), 77 (4.0), and 225 (4.9) g/kg of DM, respectively. The corresponding NDF values were 473 (42.0), 458 (33.7), and 268 (12.8) g/kg of DM. The mean ME concentrations of the grass and maize silage were 12.1 and 11.5 MJ/kg of DM, respectively.

Concentrate feeding method had no effect on mean daily concentrate or total DMI (kg/cow per day; Table 2). However, cows on the PMR and PMR-Y treatments had greater ($P < 0.05$) forage DMI (kg/cow per day) than those on OPF-F or OPF-Y. We observed no effect of treatment on mean daily yields (kg/cow per day) of milk, milk fat, milk protein, or milk fat-plus-protein. Similarly, treatment had no effect on milk fat, protein, or lactose concentrations (g/kg), or on milk energy concentration (MJ/kg) or output (MJ/cow per day). However, there were tendencies toward significance for milk fat ($P = 0.078$) and energy concentrations ($P = 0.083$; Table 2).

Concentrate feeding method had no effect on mean daily ME intake (MJ/cow per day), ME requirement (MJ/cow per day), MEb (MJ/cow per day), mean BW (kg), final BW (kg), mean BCS, or final BCS of the cows (Table 3). However, there was a tendency ($P = 0.074$) toward significance for mean BCS. Treatment had no effect on days to onset of luteal activity, days to first observed heat, or conception rate to first service (Table 3).

Concentrate feeding method did not affect concentrations of BHB [mean value across the CFM of 0.51 (SEM 0.028) mM], total protein [62.6 (2.45) g/L], urea [3.56 (0.122) mM], or nonesterified fatty acids [0.54 (0.043) mEq/L] in blood serum or on glucose concentration [3.12 (0.038) mM] in blood plasma. All blood metabolite variables were affected ($P < 0.001$) by week postpartum, and we detected a treatment $\times$ week postpartum interaction ($P < 0.05$) for urea concentration.

When analyzed using weekly data, CFM had no effect on mean daily milk yields of the cows during the experiment (Figure 1), whereas forage DMI was affected ($P < 0.001$) by CFM (Figure 2). Mean daily milk yield and forage DMI were affected ($P < 0.001$) by week postpartum (Figures 1 and 2, respectively). We

Table 2. Effect of concentrate feeding method on DMI, milk production, and milk composition during wk 2 to 21 postpartum

Item	Concentrate feeding method ¹				SEM	P-value
	OPF-F	OPF-Y	PMR-Y	PMR		
DMI (kg/cow per day)						
Silage	11.8 ^b	11.5 ^b	13.1 ^a	12.8 ^a	0.24	<0.001
Concentrate	10.3	10.6	9.9	9.5	0.40	0.202
Total	22.2	22.1	23.0	22.3	0.43	0.465
Milk yield (kg/cow per day)	40.7	41.7	39.3	39.4	0.90	0.309
Milk composition						
Fat (g/kg)	42.0	40.8	42.5	44.0	0.86	0.078
Protein (g/kg)	32.6	32.8	33.1	33.2	0.39	0.731
Lactose (g/kg)	46.3	46.1	46.4	46.3	0.20	0.758
Energy ² (MJ/kg)	3.16	3.11	3.19	3.24	0.036	0.083
Milk fat yield (kg/cow per day)	1.72	1.70	1.66	1.71	0.048	0.759
Milk protein yield (kg/cow per day)	1.32	1.37	1.30	1.31	0.033	0.523
Milk fat plus protein yield (kg/cow per day)	3.00	3.06	2.96	3.04	0.089	0.828
Milk energy output (MJ/cow per day)	128	130	125	128	3.6	0.736

^{a,b}Means within a row with different superscripts differ ($P < 0.05$).

¹OPF-F = out-of-parlor feeding at a flat rate; OPF-Y = out-of-parlor feeding using a yield-based approach; PMR-Y = partial mixed ration plus additional concentrate offered using a yield-based approach; PMR = partial mixed ration.

²Calculated according to Tyrrell and Reid (1965).

detected no treatment $\times$ week postpartum interaction ($P > 0.05$) for mean daily milk yield (Figure 1), but there was a treatment $\times$ week postpartum interaction ($P = 0.002$) for mean forage DMI (Figure 2).

When the silage and total DMI of the cows in each CFM were plotted against their mean daily milk yields (Figure 3), we detected a linear increase ($P = 0.019$) in silage DMI of cows in the OPF-F treatment with increasing milk yields but no linear relationship ($P > 0.05$) between silage and mean daily milk yield for OPF-Y, PMR-Y, or PMR. Total DMI increased linearly as milk yields increased for OPF-Y ($P < 0.001$) and PMR-Y ($P = 0.004$), but no relationship ($P > 0.05$) was observed for OPF-F or PMR. There was, however, a tendency ($P = 0.061$) toward a linear increase in total DMI for OPF-F (Figure 3). We detected linear decreases in MEb as milk yields increased for

OPF-F ($P < 0.001$) and PMR ($P = 0.002$) but no linear relationship ($P > 0.05$) between these variables for OPF-Y or PMR-Y. However, there was a tendency ($P = 0.055$) toward a relationship for the latter PMR-Y treatment (Figure 4).

DISCUSSION

The increase in milk yield potentials within many dairy cow populations has been accompanied by a corresponding increase in concentrate feeding. However, the greater cost of concentrates compared with forages (e.g., Finneran et al., 2012) means that it is important that concentrates are used efficiently. Concentrates are generally offered via a range of feeding methods on farms, comprising different feeding systems (e.g., mixed rations versus separate feeding of concentrate

Table 3. Effect of concentrate feeding method on ME variables, BW, BCS, and reproductive performance of cows during wk 2 to 21 postpartum

Item	Concentrate feeding method ¹				SEM	P-value
	OPF-F	OPF-Y	PMR-Y	PMR		
Mean ME intake (MJ/cow per day)	277	279	288	280	6.1	0.583
Mean ME requirement (MJ/cow per day)	285	287	280	284	6.8	0.920
Mean ME balance (MJ/cow per day)	-8	-8	8	-4	5.7	0.173
Mean BW (kg)	622	626	634	623	8.4	0.701
Final BW (kg)	627	629	640	637	10.0	0.780
Mean BCS	2.4	2.4	2.5	2.4	0.42	0.074
Final BCS	2.3	2.3	2.4	2.3	0.55	0.862
Days to onset of luteal activity ²	26	29	34	33	3.2	0.261
Conception rate to first service (proportion of cows served)	0.42	0.35	0.33	0.17	0.103	0.371

¹OPF-F = out-of-parlor feeding at a flat rate; OPF-Y = out-of-parlor feeding using a yield-based approach; PMR-Y = partial mixed ration plus additional concentrate offered using a yield-based approach; PMR = partial mixed ration.

²Defined as the first day of at least 2 consecutive milk progesterone concentrations ≥ 3 ng/mL.

Figure 1. Effect of concentrate feeding method (CFM) on mean (and SEM) daily milk yields during wk 2 to 21 postpartum. OPF-F = out-of-parlor feeding at a flat-rate; OPF-Y = out-of-parlor feeding using a yield-based approach; PMR-Y = partial mixed ration plus additional concentrate offered using a yield-based approach; PMR = partial mixed ration.

Figure 2. Effect of concentrate feeding method (CFM) on mean (and SEM) silage DMI of cows during wk 2 to 21 postpartum. OPF-F = out-of-parlor feeding at a flat-rate; OPF-Y = out-of-parlor feeding using a yield-based approach; PMR-Y = partial mixed ration plus additional concentrate offered using a yield-based approach; PMR = partial mixed ration.

Figure 3. Linear regression analysis between mean daily DMI (kg/cow per day) and milk yields for cows managed on 4 concentrate feeding methods during wk 2 to 21 postpartum.

Figure 4. Linear regression analysis between mean ME balance (MEb; MJ/cow per day) and mean daily milk yields for cows managed on 4 concentrate feeding methods during wk 2 to 21 postpartum.

and forage) and allocation strategies (e.g., flat rate versus feed-to-yield), and it is possible that the CFM used may affect concentrate use efficiency. Despite this, there is a paucity of information relating to the effects of CFM on the performance of higher-yielding dairy cows (i.e., those producing approximately 40 kg of milk/day). Thus, the present study was undertaken to address the absence of information in this area.

To avoid confounding effects of differences in the quantities of concentrates offered across the CFM, an important target in this experiment was for cows on all 4 CFM to have a similar mean daily concentrate DMI during the experimental period. Although the range in concentrate intakes across the 4 treatments was greater than anticipated (1.1 kg of DM/cow per day), there was no statistically significant difference between the CFM, thus meeting the aforementioned target.

Although the term "PMR" was adopted in the current study for the PMR treatment (due to 1.0 kg of concentrate being offered daily via in-parlor feeders), over 90% of the concentrate component of the diet was offered via the mixed ration in this treatment. However, concentrates were included in the PMR at a fixed level per cow per day, rather than at a fixed ratio, as adopted in many, but not all, previous studies. This difference might appear to be relatively minor, but it could affect the intake of each dietary component, and as such, may affect milk production. For example, when concentrates are offered at a fixed ratio, cows at peak intake or those with a higher intake potential will be able to increase their concentrate intake by consuming more of the total ration, without affecting the concentrate intakes of other cows. In contrast, when concentrates are included in the diet at a fixed level per cow per day, cows with higher total DMI (due either to stage of lactation or intake potential) will consume more concentrates at a fixed level, whereas cows with lower total DMI will have a lower concentrate DM intake than those on a fixed level. For the reasons described above, the findings of the current study are not completely comparable to results of many earlier studies. Nevertheless, in a review of studies examining concentrate feeding systems, Ferris et al. (2002) concluded that, in general, total DMI tended to be higher with cows offered a TMR than for those offered concentrate separately from silage at a flat rate (e.g., Phipps et al., 1984, experiment 1; Istasse et al., 1986; Nocek et al., 1986; Dulphy et al., 1994; Agnew et al., 1996), especially in studies involving higher concentrate levels, although several other authors reported no differences in total DMI between these treatments [e.g., Stanley and Morita, 1967; Villavicencio et al., 1968; Holter et al., 1977; Phipps et al., 1984, experiment 2).

Although total DMI was unaffected by CFM, cows on PMR and PMR-Y had greater silage DMI than those on OPF-F and OPF-Y. This finding likely reflects the numerically lower concentrate DMI with these treatments (9.5 and 9.9 kg/cow per day) than for the OPF-F and OPF-Y treatments (10.3 and 10.6 kg/cow per day, respectively). Despite these small differences in concentrate intakes between the 4 treatments, the silages offered in this experiment were of high quality, which resulted in daily ME intakes being similar across the 4 CFM.

Offering concentrates mixed with silage may increase cow performance by improving the synchrony in the supply of dietary energy and RDP, which has been shown to increase the efficiency of microbial synthesis in sheep (Sinclair et al., 1993). Feeding concentrates mixed with silage has also been found to reduce the risk of rumen acidosis compared with separate feeding (Maekawa et al., 2002), and this may also contribute to improved performance. However, the out-of-parlor feeding systems used in the current study allowed concentrates to be offered separately from silage in multiple small meals throughout the day, and consequently many of the potential benefits advocated for offering mixed rations are likely to have been achieved with the treatments involving out-of-parlor feeding. Considering this, and the similar total DMI highlighted above, the overall absence of differences in milk yields between the PMR and OPF-F treatments is unsurprising. Although the results of the current study are not completely comparable to the outcomes of some previous studies due to the method used to determine concentrate inclusion levels within the PMR, they are nevertheless in general agreement with earlier studies; namely, no difference in the milk yields of either low-yielding (<25 kg/cow per day; Agnew et al., 1996; Phipps et al., 1984) or moderate-yielding (approximately 30 to 35 kg/cow per day; Yan et al., 1998; Gordon et al., 1995) cows offered concentrates either separately from forage or mixed with forage. In general, the effects on milk composition of offering concentrates mixed with forage, compared with separately from forage, are inconsistent across studies, with several authors reporting differences in either milk fat or milk protein concentrations (Stanley and Morita, 1967; Gordon et al., 1995; Yan et al., 1998), whereas others reported no such effects (Dulphy et al., 1994; Villavicencio et al., 1968; Holter et al., 1977; Nocek et al., 1986; Agnew et al., 1996). The findings from the current study are in agreement with the latter group of authors.

The overall absence of a difference in total DMI and milk yields between the PMR and OPF-F treatments may also partly reflect the proportion of concentrate

in the total diet offered to cows on these treatments (0.43 and 0.46, respectively). For example, Phipps et al. (1984) reported greater total DMI for cows offered a TMR with a concentrate-to-forage ratio of 60:40 (on a DM basis) *ad libitum* than for those offered the same concentrates and forage separately, but found no difference between these treatments when the concentrate-to-forage ratio in the TMR was 50:50. In accord with this finding, Istasse et al. (1986) reported greater total DMI for a TMR diet versus a separately offered diet, with this difference being greater when the concentrate proportion in the diet was 0.65 (difference of 3.7 kg/cow per day) rather than 0.40 (1.6 kg/cow per day). This finding for the latter study resulted in greater milk yields for the TMR feeding method at a concentrate proportion of 0.65, but no difference between the treatments at the 0.40 proportion. In agreement with this, Ferris et al. (2002), in a review of several studies in which the forage and concentrate components of the diet were offered either separately or mixed, concluded that differences in milk production were most likely to be observed at a concentrate DM proportion in the total diet DM of >0.60 . Thus, at concentrate proportions similar to those in the current study, CFM is unlikely to have a large effect on total DMI or milk yields.

Whereas the OPF-F and PMR treatments allowed the effects of offering concentrates either mixed with or separately from the forage component of the diet to be examined, neither treatment involved offering concentrates to individual cows based on their milk yields. In contrast, cows within the OPF-Y and PMR-Y treatments were offered concentrates according to their milk yields in early lactation and their expected milk yields throughout early to mid lactation. The adoption of similar systems on commercial dairy farms has been facilitated by computer software packages that directly link concentrate feeding systems to milking parlor software. Indeed, the PMR-Y treatment involved an approach that has become increasingly common on UK dairy farms; that is, offering a basal diet consisting of a mixed ration designed to support the maintenance energy requirements of the cows plus a specific milk yield, with individual cows then offered additional concentrates at a specific feed rate to support milk yields produced above those sustained by the basal diet. This additional concentrate is generally offered via either in-parlor or out-of-parlor feeding systems. Although concentrates with OPF-Y and PMR-Y in the current study were offered according to 3 predetermined concentrate allocation curves (to ensure similar concentrate intakes for cows on all 4 treatments), this approach still encompassed the broad feed-to-yield principle; that is, aligning concentrate allocations with milk yields.

The results for the OPF-F and OPF-Y treatments, which differed only in how concentrates were allocated to individual cows via the out-of-parlor feeders, were unequivocal—there was no difference between these treatments in either milk production or milk composition. This outcome reflects the similar DM and ME intakes of cows on these treatments and the absence of differences in BW and BCS. Similarly, a comparison of PMR with PMR-Y provided no evidence of improved cow performance through the adoption of a precision concentrate feeding approach (PMR-Y). These findings are in agreement with those of several authors (e.g., Gordon, 1982; Taylor and Leaver, 1984a), who also reported no differences in the milk yields of cows offered concentrates on a flat-rate or a feed-to-yield basis.

Although we might have expected that cows on the OPF-Y and PMR-Y treatments would show improved performance over those on the OPF-F or PMR treatments, due to the energy requirements of cows on the 2 former treatments being more closely met, no such effect was observed. Indeed, Gordon (1984) challenged the validity of this assumption for cows offered a forage diet *ad libitum*. For example, an important supposition in this hypothesis is that higher-yielding cows will exhibit a greater milk yield response to each additional kilogram of concentrate offered than will lower-yielding cows. However, Gordon (1984) found that the marginal milk yield response to concentrates was similar for high-yielding and low-yielding cows, which may explain the absence of a difference in milk yields between treatments in which concentrates were offered to yield, and those in which concentrates were offered at a flat rate.

Although CFM had no effect on milk yield, there was a tendency for cows on the OPF-Y treatment to produce milk with a lower fat concentration. This finding likely reflects the lower forage-to-concentrate ratio with this treatment (1.08), compared with the other treatments (1.15, 1.32, and 1.35 for OPF-F, PMR-Y, and PMR, respectively, and an associated decrease in rumen pH (Agle et al., 2010). Despite this trend in milk fat concentration, milk fat-plus-protein yield did not differ between the CFM.

The similar mean and final BCS of the cows in all 4 CFM suggests similar extents of body tissue mobilization or deposition, or both, with each CFM during the study. This finding is in accord with the lack of an effect on any of the ME variables examined and the similar milk yields across the CFM. This outcome is also supported by the absence of an effect on the blood serum concentrations of nonesterified fatty acids, which is indicative of the extent of lipolysis in adipose tissue in dairy cows (e.g., Rukkwamsuk et al., 1999), and also the similar blood serum BHB concentrations across

the CFM. Considering the overall absence of effects of treatments on the intakes, milk yields, and body tissue status of the cows, the lack of an effect on fertility performance was not unexpected.

In addition to examining the overall effects of CFM, we also examined the intake and MEb responses of the individual cows to increasing milk yields within each treatment. As concentrates are normally offered according to milk yield within precision concentrate feeding systems, an understanding of these relationships is important. The increased silage DMI with increasing mean daily milk yields for the OPF-F treatment was as expected; namely, that higher-yielding cows would have greater forage intakes than lower-yielding cows when all cows were offered the same quantity of concentrates. Despite this, the linear increase in silage DMI was generally small ($R^2 = 0.21$, $P < 0.05$; as shown in Figure 3), and consequently resulted in no linear increase in total DMI with increasing milk yields for this treatment. The contrasting findings for the PMR-Y and OPF-Y treatments (i.e., a linear increase in total DMI and lack of a relationship for silage DMI) indicate that the silage intakes of cows in this group remained generally constant as concentrate intakes and milk yields increased. Therefore, cows offered greater quantities of concentrates based on their requirements for milk production had similar silage intakes to lower-yielding cows offered less concentrates. This outcome does not mean that dietary substitution did not occur with increasing milk yield, but rather suggests that the extent of substitution was similar for both higher-yielding cows (which were also offered more concentrates) and lower-yielding cows. Considering this, it seems likely that adopting a common value for the milk yield sustained from a basal diet for all cows regardless of their milk yields is appropriate. The linear decreases in MEb with increasing milk yields, and the lack of linear relationships between these variables for OPF-Y and PMR-Y, were in line with expectations; namely, that offering concentrates to cows based on their specific requirements for milk production would result in their energy requirements for milk production being more closely met.

An important consideration in the interpretation of results of the current study is that all cows were at similar stages of lactation throughout the study, reflecting their narrow range of calving dates (i.e., 129 d). This is in contrast to the broader range in calving dates common on many farms. In this scenario, if cows of differing stages of lactation (early, mid, and late) are offered concentrates on a flat-rate basis, early-lactation cows may be underfed, whereas late-lactation cows may be overfed, resulting in the latter cows partitioning relatively more energy to body tissue deposition. Thus, it is suggested that if flat-rate feeding is adopted in herds

with spread calving patterns, grouping cows according to their stage of lactation and milk yields is essential.

CONCLUSIONS

Concentrate feeding method had no effect on the performance of high-yielding cows in early to mid lactation, when all cows were offered the same amount of concentrate in addition to a basal diet offered ad libitum. Thus, it is likely that feeding method will have little effect on the performance of cows at similar stages of lactation offered concentrates and silage at ratios similar to those offered in this study.

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