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Within-Day Feeding Behavior of Lactating Dairy Cows Measured Using a Real-Time Control System

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ABSTRACT

The suitability of a statistical model for describing within-day feeding behavior, and potential relationships between model parameters and commonly measured experimental variables were examined. Forty multiparous, midlactation Holstein cows were fed using a real-time control system to record the date of each visit to a feeder, entrance time, exit time, and feed consumed over a 6-wk period. Daily feed consumption, number of visits, meal duration, and within-visit rate of food intake were then calculated. Two peaks in within-day rates of feed intake were indicated, suggesting that feeding activity was randomly distributed around each peak, that is, binormal. Parameters describing the distributions (means, standard deviations, and the percentage of total feeding activity associated with each peak) were estimated. An adjusted average of 91% of the variation in within-day feeding activity was explained by the binormal model. Relationships between model parameters and commonly measured experimental variables were also identified; behavioral traits were correlated with total feed intake. Feeding activity patterns in literature data were also amenable to reanalysis by the binormal model. Lactating cows consistently exhibited a distinct diurnal pattern in feeding activity; they were most active near sunrise and again near sunset (crepuscular). Effects of various management operations (e.g., feeding and milking times and frequencies, and lighting) on within-day feeding patterns remain to be established, although a statistical model for evaluating them is now available. The patterns may have important implications for scheduling management activities to maximize feed intake and production.
(**Key words:** dairy cow, feeding behavior, model)

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INTRODUCTION

Various management strategies are used by dairy producers to increase milk yield. These include increased feeding and milking frequencies, cooling systems, artificial lighting, processing of feedstuffs, and manipulation of diet composition. These tools, or combinations of them, have improved cow performance by increasing yield of milk or its components, reducing environmental impact or improving reproduction. Feeding frequency was reported to affect daily patterns of DMI and water consumption when a TMR was fed to dairy cows in their first lactation (Nocek and Braund, 1985); however, the effects of most of these management tools on daily eating behavior patterns are not yet known. Dairy producers can use knowledge of animal behavior to improve cow well-being and performance.

Feeding behavior of lactating dairy cows fed ad libitum can be measured in many ways. Time-lapse photography (Vasilatos and Wangsness, 1980), closed-circuit television (Hedlund and Rolls, 1977), electronic recording or visual observation (Penning, 1983), hourly consumption patterns (Nocek and Braund, 1985), and automatic feeders with identification or automatic bitemeters (Delagarde et al., 1999) have all been used. Of these, only automatic feeders with an identification system can handle and record data from large numbers of cows in a free-stall housing situation for long periods.

Although meal frequency and intermeal intervals have been studied (Tolkamp et al., 1998, 2000; DeVries et al., 2003), within-day feeding patterns of cows in free-stalls have only been qualitatively analyzed in a small number of experiments or data have remained unpublished because models to describe them were unavailable. Statistical models are needed to evaluate these data and allow the proportion of the ration consumed and the rate of feed intake to be measured throughout the day.

Our objective was to examine the suitability of a statistical model for describing within-day feeding behavior, and potential relationships between model parameters and commonly measured experimental variables.

Table 1. Composition of experimental diet.

Item	(% of DM)
Barley	12.9
Citrus pulp	3.3
Corn	11.7
Cottonseed	3.6
Fish meal	0.5
Corn gluten meal	0.6
Corn gluten feed	4.4
Rapeseed meal	3.5
Sorghum	6.5
Soybean meal	4.4
Soybean oil	0.1
Sunflower meal	3.3
Wheat bran	9.2
Corn silage	15.0
Legume hay	3.5
Oat hay	3.5
Wheat silage	9.5
Wheat straw	2.3
Urea	0.3
Ammonium sulfate	0.1
Magnesium oxide	0.1
Salt	0.5
Calcium carbonate	1.1
Vitamins and minerals[1]	0.1
DM, %	56.0
NE_L, Mcal/kg of DM	1.67
CP	16.9
NDF	34.2
ADF	18.8
P	0.5
Ca	0.8

[1]Contained 2200 IU of vitamin A/g, 2000 IU of vitamin D/g, 15 IU of vitamin E/g, 6000 ppm Zn, 6000 ppm Mn, 2000 ppm Fe, 1500 ppm Cu, 120 ppm I, 20 ppm Co, and 50 ppm Se.

MATERIALS AND METHODS

Cows and Management

The guidelines of Israel for animal care and use were followed. Forty multiparous Holstein cows in midlactation [627 ± 55 kg BW; 165 ± 5 DIM (mean ± SD)] were used. Cows were housed loose in a covered barn with adjacent pen yards. They had free access to water, were milked thrice daily (0500, 1400, and 2000 h), and were fed a TMR once daily at 1100 h for ad libitum intake. Ingredient composition of the TMR is in Table 1. Diets were formulated to meet stated nutrient requirements for lactating dairy cows (NRC, 1989).

Milk weights were automatically recorded at each milking (Afimilk, Kibbutz Afikim, Israel). Milk was sampled at each milking every second week, preserved with 2-bromo-2-nitropropane-1,3-diol, and stored at 4°C until analyzed for fat, CP, and lactose by infrared analysis by the Israel Cattle Breeders Association (Milk Recording Laboratory, Bitan-Aharon, Israel). Dry matter intake was measured and recorded daily for 6 wk. During the trial, mean sunrise and sunset were at 0508 and 1818 h, respectively.

Recording of Feeding Behavior

A real-time control system for individual food intake of group-housed lactating dairy cows was used (Halachmi et al., 1998). The system consisted of 40 feeding stations, one for each cow. Each station was equipped with: 1) individual identification system (TIRIS, Dallas, TX) that allowed each cow to enter a specific station only, by using a pneumatic system, and to record the time of each visit; and 2) scales that measured the weight of the feed trough continuously, and recorded entrance and exit weights. All electronic and pneumatic components were connected directly to a single, reliable, industrial programmable logic controller.

These systems enabled measurement and recording of the date of each visit, entrance time, exit time, and feed consumed. Later, daily feed consumption, number of visits, meal duration, and rate of food intake were calculated from the recorded database.

Model Description and Statistical Analyses

Cattle have a distinct diurnal grazing pattern (Albright, 1993); i.e., they are most active at sunrise and again at sunset. Hughes and Reid (1951) concluded that, in both cattle and sheep, the most constant periods of grazing occur in the early morning and in late afternoon until dusk. They also noted that commencement of early morning grazing was correlated to sunrise and cessation of evening grazing to sunset, and that between these primary periods, no definite pattern of grazing could be recognized in the daytime. Sheppard et al. (1957) found that major grazing periods of beef steers were in the morning and evening, with a minor period occurring during midday. Vasilatos and Wangsness (1980) 2 peaks in within-day feeding activity of lactating dairy cows fed twice daily, and it was minimal at midnight. Nocek and Braund (1985) again found that mean hourly rates of DMI in lactating cows fed 1, 2, 4, or 8 times daily were minimal between 1801 and 0559 h. As others have reported, rates of DMI seemed to peak in early morning and late afternoon.

Based on these observations, we defined the within-day feeding interval as between successive midnights (proportion of the day between 0 and 1 to the nearest 0.0001, Noon = 0.5000). Day-to-day DMI varied; therefore, within-day intake was expressed as a percentage of total consumption for each day (0 to 100, Figure 1). For each visit to the feeder, data consisted of its midpoint [proportion of the day (independent variable), (exit time minus entry time)/2] and the cumulative percentage of intake for that day to that time (dependent variable).

Evidence for 2 peaks in within-day rates of DMI suggested the hypothesis that feeding activity was ran-

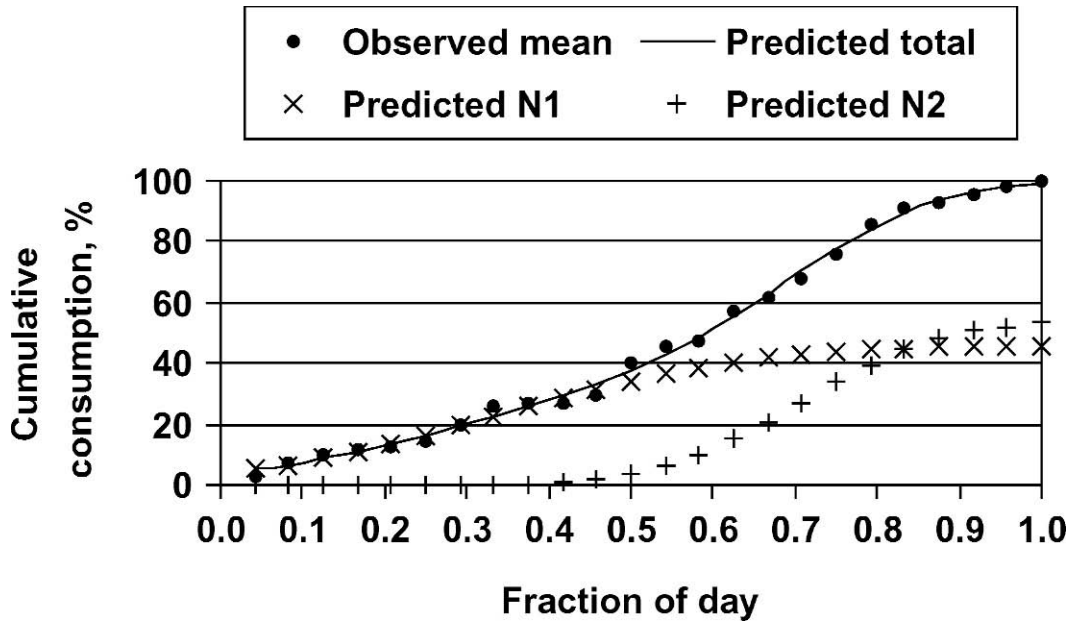

Figure 1. Cumulative feed consumption, expressed as a percentage of total daily intake, throughout the day (0 and 1 are successive midnights; noon = 0.5); N1 = first component normal curve, N2 = second component normal curve, and Total = sum of the 2 components. Curves were generated using hourly data and parameter estimates from Table 7.

domly distributed around each peak; i.e., binormal (Figure 2). Parameters describing the distributions [their means (μ_1, μ_2) and standard deviations (s_1, s_2), and the percentage of total feeding activity that was associated with each peak (a_1, a_2)] could then be estimated for each cow. For comparison, residual mean square and

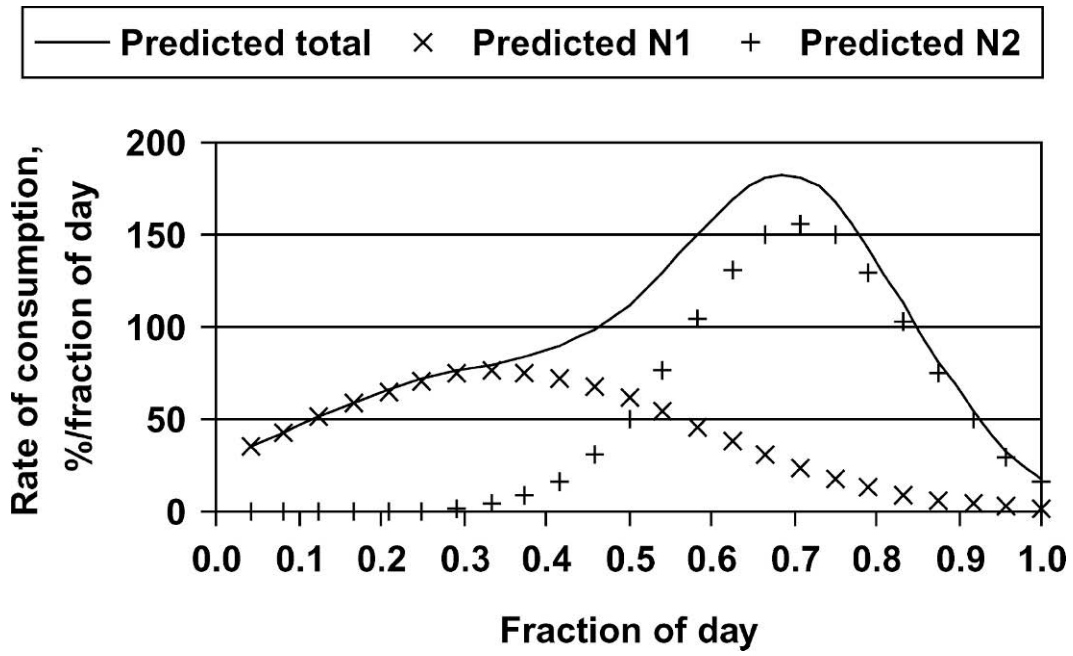

Figure 2. Rate of feed consumption, expressed as a percentage of total daily intake, throughout the day (0 and 1 are successive midnights; noon = 0.5); N1 = first component normal curve, N2 = second component normal curve, and Total = sum of the 2 components. Curves were generated using hourly data and parameter estimates from Table 7.

Table 2. Real-time control system statistics, and milk yields and milk composition of cows during the experiment (n = 40).

Measure	Mean	SD
Time spent eating, min/d	170	27
Number of visits	12.0	3.1
Total feed intake (as fed), kg/d	36.0	4.2
Milk, kg/d	28.4	5.6
Milk protein, %	3.21	0.26
Milk protein, kg/d	1.05	0.20
Milk fat, %	3.21	0.38
Milk fat, kg/d	0.90	0.15
Milk lactose, %	4.38	0.22
Milk lactose, kg/d	1.41	0.14

parameter significance were also examined for 1-peak and 3-peak models.

The cumulative normal distribution function [$P(x)$] does not have an analytical solution; therefore, a polynomial approximation of the standard normal was used (26.2.17; National Bureau of Standards, 1972). The equation was: $P(x) = 1 - Z(x)(b_1t + b_2t^2 + b_3t^3 + b_4t^4 + b_5t^5) + \varepsilon(x)$ [the residual], where $Z(x) = (1/(2\pi)^{1/2})\exp(-x^2/2)$, $t = 1/(1 + px)$, $P = 0.2316419$, $b_1 = 0.319381530$, $b_2 = -0.356563782$, $b_3 = 1.781477937$, $b_4 = -1.821255978$, and $b_5 = 1.330274429$. This equation is valid for $0 \leq x < \infty$ and $|\ \varepsilon(x)\ | < 7.5 \times 10^{-8}$. A nonlinear regression program (Sherrod, 2000) estimated μ_1, μ_2, s_1, s_2, and a_1; and a_2 was calculated as $100 - a_1$. For comparison, similar analyses were conducted for the 24-h mean data of Nocek and Braund (1985), Dado and Allen (1994), and Tolkamp et al. (2000). When not provided, average sunrise and sunset times were based on US Naval Observatory data.

Correlations between model parameters and experimental variables were calculated using the regression procedure of SAS (SAS Institute, 1985).

RESULTS AND DISCUSSION

Cow Performance

Standard analyses of data (14,113 records) from the real-time control system yielded several statistics: time spent eating, number of visits, and total feed intake (Table 2). Average time spent eating (170 min/d) was in the range reported by others (Hedlund and Rolls, 1977; Vasilatos and Wangsness, 1980; Tolkamp and Kyriazakis, 1999). Number of visits averaged 12/d, higher than the 6 to 7 meals/d reported by others (Tolkamp et al., 2000; DeVries et al., 2003). Number of visits and the average meal duration probably differed because cows were exposed to hot weather during the Israeli summer.

Milk production and composition data are also included in Table 2. Correlations between these statistics are in Table 3. Milk yield increased ($P < 0.010$) with time spent eating and tended ($P < 0.053$) to increase with feed intake, but was not correlated ($P > 0.100$) with number of visits. These results agree with those of Dado and Allen (1994) for lactating Holsteins and Ingrand et al. (2000) for lactating Charolais. Because time spent eating was the most important of the factors affecting milk yield, producers may increase performance by encouraging lactating dairy cows to spend more time eating.

Modeling Results

Average residual mean squares for mononormal, binormal, and trinormal distributions for data of 28 cows (comparisons were not possible for 12 of the 40 cows) were 95.4, 76.6 (a reduction of 20%), and 75.8 (a further reduction of 1%), respectively. All parameters of the trinormal model (a_1, a_2, μ_1, μ_2, μ_3, s_1, s_2, and s_3) were significant for only 2 of 40 cows; therefore, the binormal model was selected and results for it, based on a mean of 353 observations per cow, are summarized in Table 4. On average, the binormal model explained an adjusted 91% of the variation in within-day feeding behavior. Cumulative percentage of feed consumed throughout the day was explained, with an average deviation (absolute value of the difference between observed and predicted values) of 6.3 percentage units, by 5 parameters with straightforward biological interpretations.

Table 3. Correlations between real-time control system statistics and yields of milk and milk components (n = 40).

Measure		Milk yield (kg/d)	Milk protein (%)	Milk protein (kg/d)	Milk fat (%)	Milk fat (kg/d)	Milk lactose (%)	Milk lactose (kg/d)
Time spent eating	r	0.400	–0.121	–0.175	–0.130	0.415	0.346	0.070
	P	0.010	0.458	0.280	0.422	0.008	0.029	0.667
No. of visits	r	0.124	–0.059	–0.144	–0.114	0.048	0.030	–0.100
	P	0.444	0.718	0.376	0.485	0.771	0.856	0.539
Total feed intake	r	0.308	–0.028	–0.076	–0.087	0.334	0.188	0.114
	P	0.053	0.865	0.640	0.593	0.035	0.246	0.482

Table 4. Binormal model parameter estimates and statistics.

Item	Mean	SD	n[1]	Minimum	Median	Maximum
Adjusted R-squared[2]	0.915	0.033	40	0.815	0.924	0.970
Average deviation[3]	6.30	1.10	40	4.10	6.10	9.86
First normal curve[4]						
μ_1	0.34	0.08	30	0.12	0.35	0.55
s_1	0.28	0.03	32	0.15	0.29	0.33
a_1	61	12	30	32	61	90
Second normal curve						
μ_2	0.69	0.04	40	0.57	0.70	0.77
s_2	0.11	0.04	34	0.04	0.11	0.20
a_2 (= 100 − a_1)	39	12	30	10	39	68

[1]Number of cows for which estimates differed from 0 ($P < 0.05$) and were included in table.

[2]Adjusted coefficient of multiple determination computed based on the number of parameters in the model (p) and the number of observations (n) according to the formula: $1 - [(n - 1)/(n - p)] \times (SSE/SSTotal)$.

[3]Average, over all observations, of the absolute value of the difference between observed and predicted values of the dependent variable (cumulative percentage of daily feed consumption).

[4]Means (μ_1, μ_2), standard deviations (s_1, s_2), and percentages of total feeding activity (a_1, a_2) associated with each peak.

The morning peak in feeding activity (μ_1) occurred at 0814 h (Table 4), just over 3 h after mean sunrise (0508 h). It ranged from 0255 to 1317 h. Afternoon feeding activity peaked (μ_2) at 1634 h, almost 2 h before mean sunset (1818 h), and ranged from 1345 to 1828 h. Major morning and afternoon peaks in feeding activity suggest that lactating cows in a dry lot have diurnal eating patterns similar to those of grazing cattle that were described by Albright (1993).

Standard deviations (s_1, s_2) of the binormal distribution of feeding activity (Table 4) were 6:44 and 2:38, respectively; therefore, feeding activity associated with the morning peak occurred over a longer period than that associated with the afternoon peak. On average, 61% of total feeding activity was associated with the morning peak (a_1) and the remainder (39%) with the afternoon peak (a_2).

Relationships between model parameters are in Table 5. The higher the percentage of total consumption associated with the morning peak in feeding activity, the later and broader it was; however, the afternoon peak, although also later, was narrower. Correlations between measured experimental variables and binormal model parameter estimates (Table 6) suggested that total feed intake increased as the proportion of consumption associated with the first peak in activity decreased. Increased feed intake was also positively correlated with the standard deviation of the second peak. These relationships are consistent with short-term control of feed intake; i.e., cows can consume more feed by distributing their eating

Table 5. Correlation coefficients between binormal parameter estimates.

Variable[1]		s_1	a_1	μ_2	s_2	a_2
μ_1	r	0.325	0.813	0.699	−0.568	−0.813
	P	0.080	**	**	**	**
	n[2]	30	29	30	28	29
s_1	r		0.418	−0.106	−0.424	−0.418
	P		0.022	0.564	0.019	0.022
	n		30	32	30	30
a_1	r			0.601	−0.844	−1.000
	P			**	**	**
	n			30	28	30
μ_2	r				−0.680	−0.601
	P				**	**
	n				34	30
s_2	r					−0.844
	P					**
	n					28

[1]Means (μ_1, μ_2), standard deviations (s_1, s_2), and percentages of total feeding activity (a_1, a_2) associated with each peak.

[2]Number of cows for which estimates differed from 0 ($P < 0.05$) and were included in the table.

**$P < 0.01$.

Table 6. Correlation between real-time control system measured variables and binormal model parameter estimates.[1]

Variable		μ_1	s_1	a_1	μ_2	s_2	a_2
Time spent eating	r	0.087	0.086	–0.118	–0.259	0.216	0.118
	P	0.649	0.640	0.534	0.106	0.219	0.534
	n[2]	30	32	30	40	34	30
No. of visits	r	0.332	–0.195	–0.078	0.363	0.215	0.078
	P	0.073	0.285	0.680	0.021	0.223	0.680
	n	30	32	30	40	34	30
Total feed intake	r	0.060	0.014	–0.135	–0.257	0.378	0.135
	P	0.751	0.940	0.048	0.110	0.027	0.478
	n	30	32	30	40	34	30

[1]Means (μ_1, μ_2), standard deviations (s_1, s_2), and percentages of total feeding activity (a_1, a_2) associated with each peak.

[2]Number of cows for which estimates differed from 0 ($P < 0.05$) and were included in the table.

over more of the day. Number of visits was positively correlated with time of the second peak in feeding activity and tended to be positively correlated with time of the first peak. Milk yield and composition measures were not correlated with model parameters.

Data for the present experiment were restructured into 24 hourly means, across cows and days, and reanalyzed for comparison with literature data (Table 7). The proportions of variance that were explained by the binormal model, and average deviations, were similar across studies. Feeding activity peaks usually occurred within 3 h of either sunrise or sunset. When the first feeding occurred before sunrise so did the first peak of feeding activity. It is interesting that this same feeding activity pattern was apparent in the data of Dado and Allen (1994) despite the fact that their experiment was conducted under continuous lighting conditions in a tie-stall barn with no windows. A TMR had been offered for ad libitum intake at 0300 and 1500 h. Perhaps uninhibited feeding activity of lactating cows exhibits a diurnal rhythm, like rumination (Murphy et al., 1983), not greatly affected by other variables.

The one case where the first peak in feeding activity occurred almost 5 h after sunrise (Tolkamp et al., 2000) is easily explained. Cows were locked out of their feeding passage between approximately 0800 and 0930 h (0.333 and 0.396 of the day, respectively).

Although Nocek and Braund (1985) concluded that diurnal patterns of DMI varied with feeding frequency, no significant ($P < 0.10$, their definition) effects on measures of behavior were detected. Reanalyses of their data here suggested that the first peak in feeding activity tended ($P = 0.074$) to decrease linearly as feeding frequency increased.

CONCLUSIONS

The binormal model was suitable for describing within-day feeding behavior of lactating cows. Relation-

Table 7. Comparison of present results with data from others fitted to the binormal model of within-day feeding behavior.[1]

Reference	Mean sunrise	Mean sunset	Adjusted R-squared[2]	Average deviation[3]	μ_1	s_1	a_1	μ_2	s_2	a_2
Present experiment[4]	0.214	0.763	0.996	1.52	0.341	0.241	45.9	0.708	0.138	54.1
Nocek and Braund (1985); 1×[5]	0.313	0.715	0.997	1.42	0.211	0.127	30.8	0.587	0.196	69.2
Nocek and Braund (1985); 2×	0.313	0.715	0.998	0.99	0.216	0.130	35.2	0.605	0.191	64.8
Nocek and Braund (1985); 4×	0.313	0.715	0.996	1.40	0.156	0.130	28.2	0.568	0.201	71.8
Nocek and Braund (1985); 8×	0.313	0.715	0.997	1.37	0.197	0.130	30.6	0.588	0.212	69.4
Dado and Allen (1994)	0.336	0.730	0.995	1.60	0.223	0.115	31.0	0.698	0.190	69.0
Tolkamp et al. (2000)	0.291	0.726	0.998	0.93	0.491	0.260	83.4	0.768	0.090	16.6

[1]Means (μ_1, μ_2), standard deviations (s_1, s_2), and percentages of total feeding activity (a_1, a_2) associated with each peak. Times of sunrise and sunset are expressed as fractions of a 24-h day.

[2]Adjusted coefficient of multiple determination computed based on the number of parameters in the model (p = 5) and the number of observations (n = 24) according to the formula: $1 - [(n - 1)/(n - p)] \times (SSE/SSTotal)$.

[3]Average, over all observations, of the absolute value of the difference between observed and predicted values of the dependent variable (cumulative percentage of daily feed consumption).

[4]Based on cumulative percentage consumed during each hour of the day across 1163 cow days so data would be comparable to those of Nocek and Braund (1985), Dado and Allen (1994), and Tolkamp et al. (2000).

[5]Feeding frequency; trend ($P < 0.074$) toward a linear reduction in μ_1 as feeding frequency increased. Once-daily feedings were at 0600 h.

ships between model parameters and commonly measured experimental variables were also identified, and suggested that behavioral traits were associated with total feed intake. Effects of various management operations (e.g., feeding and milking times and frequencies, and lighting) on within-day feeding patterns remain to be established, although a statistical model for testing them is now available. The patterns may have important implications for scheduling management activities to maximize feed intake and production.

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