Analysis of Feeding and Drinking Patterns of Dairy Cows in Two Cow Traffic Situations in Automatic Milking Systems

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ABSTRACT

With increasing possibilities for obtaining online information for individual cows, systems for individual management can be developed. Feeding and drinking patterns from automatically obtained records may be valuable input information in these systems. With the aim of evaluating appropriate mixed-distribution models for feeding and drinking events, records of 30 fresh cows from visits at feeding stations ($n = 83,249$) and water bowls ($n = 67,525$) were analyzed. Cows were either allowed a high-milking (HF) or a low-milking (LF) frequency by being subjected to controlled cow traffic with minimum milking intervals of 4 and 8 h, respectively. Milking frequency had significant effects on feeding patterns. The major part (84 to 98%) of the random variation in feeding patterns of the cows was due to individual differences between cows. It can be concluded that cows develop consistent feeding and drinking patterns over time that are characteristic for each individual cow. Based on this consistency, patterns of feeding and drinking activities have valuable potential for purposes of monitoring and decision making in individual control management systems. Use of a Weibull distribution to describe the population of intervals between meals increased the statistical fit, predicted biologically relevant starting probabilities, and estimated meal criteria that were closer to what has been published by others.

(**Key words:** feeding pattern, automatic milking, individual management, mixed distribution model)

Abbreviation key: AM = automated milking, HF = high-milking frequency, LF = low-milking frequency, LN = natural logarithm.

INTRODUCTION

Feed intake is important for maintaining the milk production and health of the dairy cow. Housing sys-

tems and management practices should promote feed intake to meet individual cow requirements. In the dairy cow and other animals, feeding is in distinct meals, and changes in feed intake occur when size of meals, interval between meals, or both are modified (Forbes, 1995). Analysis of feeding patterns has been found to be appropriate when studying the regulation of feed intake in the short term, and it has given insights into how feeding is affected by feed quality (Tolkamp et al., 2002), social environment (Nielsen, 1999), and different management practices (Albright, 1993). With computerized feeders, feeding visits can be recorded easily, which allows for detailed studies on individual feeding patterns during entire lactations. Introduction of automated milking (AM) systems not only brought on a totally new milking regimen, but it also involved a new system for feeding the cows. Existing knowledge about feeding patterns is related to dairy cows in tie stalls or stanchions (Metz, 1975; Dado and Allen, 1993) and those held in loose housing (Tolkamp et al., 2000, 2002). Little is known, however, about feeding patterns in AM systems, in which access to feeding areas is often restricted with gates somehow controlling the cow traffic. Earlier studies of feeding patterns in AM systems have used definitions of meals that have either been arbitrary or based on the assumption that meals are distributed randomly in time (Morita et al., 1996; Harms et al., 2002). Tolkamp et al. (1998) showed that the distribution of meals in time was dependent on satiety mechanisms, and, therefore, the view of randomness was criticized as lacking biological relevance. Because of satiety mechanisms, the probability that a cow will start a meal increases with the time since the last meal. Drinking patterns of dairy cows have been studied for those in tie stalls and loose housing (Andersson, 1984; Dado and Allen, 1993). No reports were in relation to AM systems. Further, Andersson (1984) pointed out that the definition of a drinking bout to a great extent affects the result when describing drinking patterns. Herein, a number of drinking occasions clustered in time are referred to as a bout. In the same way as for feeding, a model for drinking visits should be developed to find an objective definition of bouts, which

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is a prerequisite for bout-based studies of drinking patterns.

A method for analyzing feeding visits that was in accordance with satiety mechanisms was developed (Tolkamp et al., 1998; Tolkamp and Kyriazakis, 1999). Those researchers described the occurrence of meals as the presence of clusters of feeding intervals. The intervals within each cluster were assumed to be normally distributed, and a mixture of 2 or 3 Gaussian (normal) distributions was used as a model for the frequency distribution of natural logarithm (LN)-transformed feeding intervals. These distributions represented different types of intervals between feeding visits. When 2 distributions were included in the model, intervals were separated into one distribution with short within-meal intervals and another distribution with long between-meal intervals. The meal criterion (i.e., the longest interval between 2 feeding visits not separating 2 meals) was then identified as the point where an interval was assigned to both distributions with equal probabilities. In our study, it was hypothesized that the meal criterion is specific and consistent in time for individual cows. When a third distribution was added to the model, the within-meal intervals were further separated into intervals in which cows did or did not take a temporary break in feeding to visit the water bowls. Yeates et al. (2001) found that the distribution with prolonged between-meal intervals was better described with a Weibull distribution than a Gaussian distribution. Inclusion of a Weibull distribution resulted in a model that predicted that the probability of cows initiating a meal would increase with time since the last feeding occasion, which is what would be expected according to the concept of satiety.

In AM systems, in which cows visit the barn facilities voluntarily and feed is available for ad libitum intake, cows can develop an individual feeding pattern. We hypothesized that these feeding patterns are specific for each individual and consistent in time. This question is of importance because consistent feeding patterns could be used for developing an individual approach to cow traffic in AM systems. The aim of this study was 1) to find an appropriate mixture of distributions to model feeding and drinking visits, 2) to study the effects of cow traffic system and cow age on feeding and drinking visits, and 3) to study the cause of random variation in feeding patterns.

MATERIALS AND METHODS

General

A total of 30 Swedish Red and White dairy cows (first through seventh lactation) were included in the trial. Cows were kept indoors throughout the experimental

period (September 2001 to June 2002). The average milk yield was 27 kg of energy-corrected milk for cows in their first lactation ($n = 10$) and 37.9 kg of energy-corrected milk for multiparous cows ($n = 20$). Cows were offered ad libitum mixed grass silage and concentrate (75:25 ratio on DM basis) and concentrate supplied in the milking unit and in concentrate-feeding stations. Mixed grass silage (45% DM) and concentrate were accessible 24 h/d. The average daily DMI was 19.2 kg for cows in their first lactation and 24.7 kg for multiparous cows. The average daily drinking water intake was 65.3 L for cows in their first lactation and 93.3 L for multiparous cows. In the milking unit, cows were fed 0.3 kg of concentrates at each milking, and in the concentrate stations, a maximum daily amount of 10 kg was fed depending on stage of lactation. Average total number of cows in the barn during the period was 46 (with a range of 37 to 52). Cows were observed for the first part of lactation beginning 8 to 19 d after calving. Before entering the AM system, the cows spent the first 4 to 5 d after calving in a pen together with their calves. They were then transferred to a tie stall where they spent another 4 to 10 d for continual health control. After this period, they were introduced into the experimental AM system. Cows were milked 2 $\times$ daily before beginning the experiment. Cows were exposed to the AM system during previous lactations or 3 wk before calving.

Experimental Design

The study continued until wk 16 of lactation. Throughout the study, cows were subjected to controlled cow traffic by setting a minimal time limit during which they were permitted to be milked. When less than the set time limit, cows had free access to the feeding areas through control gates. Beyond this time limit, they first had to enter the milking unit to be milked before they could access the feeding area. Cows were assigned randomly according to parity (primiparous vs. multiparous) to either a high-milking frequency (HF) or low-milking frequency (LF) treatment. Cows in the HF treatment were allowed a minimum of 4 h between milking events (with a maximum of 6 milkings/24 h), whereas those in LF treatment were allowed 8 h (with a maximum of 3 milkings/24 h). Cows not milked by the AM system within 9 or 14 h for HF and LF cows, respectively, were manually brought to the AM unit for milking 2 $\times$ d. This resulted in an actual mean daily milking frequency of 3.1 and 2.1 for HF and LF treatments, respectively.

Barn Facilities

The study was performed at the University Cattle Research Center, Kungsängen in Uppsala, Sweden.

Figure 1. Schematic drawing of the experimental barn layout. B = self-grooming brush, CG = control gate, MU = automated milking unit, and W = water bowl.

The barn in which cows were housed was a loose-housing system including a resting area, 2 separate feeding areas, and a milking compartment. The resting area consisted of a total of 54 free stalls bedded with a mixture of sawdust and chopped straw on rubber mats. At the entrance to the free-stall area, there were 2 rotating brushes (DeLaval AB, Tumba, Sweden) designed for grooming the cows. From the free-stall area, cows could enter either of the 2 feeding areas through either of the 2 control gates or through the AM unit. Barn layout is presented in Figure 1. Cows exited feeding areas through self-closing gates. The milking area consisted of one AM unit (DeLaval VMS, Tumba, Sweden) and a 40-m² open waiting area in front of the unit entrance. In the AM unit, the cows were milked according to preassigned milking frequency. If they did not have permission to be milked, they were allowed to walk through the milking unit to the feeding area. The milking unit was accessible 24 h/d, except at times for system cleaning and milk handling. These inaccessible periods occurred at 0900 and 1300 h for 30 min and at 0200 h for 60 min. The alleys consisted of solid concrete floors sloping toward a central drain. Manure was removed 4×/d with automatic scrapers (DeLaval AB). Lights were illuminated at night in all areas of the barn.

Data Acquisition

In each of the 2 feeding areas, 10 feeding stations were available with mixed feed (Bio-control A/S, Rakkestad, Norway), one concentrate feeding station (DeLaval AB), one mineral bucket, one salt lick, and one

water bowl. Another 4 water bowls were placed in the free-stall area. When a cow entered the station for feeding, the front bar lowered to give access to feed in the trough; cow identity, starting time of the visit, and the weight of the feed trough were recorded. When a cow withdrew from the station, the bar rose to prevent unauthorized feed consumption by another cow; the stop-time of the visit and the weight of the feed trough were again recorded. The shortest interval that could be recorded was 3 s. The concentrate feeding stations consisted of a concentrate dispenser, an antenna for cow identification, and an automatic gate. This gate was automatically closed behind a cow that entered the feeding station to protect from attacks from barn mates during feeding. The gate stayed closed as long as the cow kept her head in the feed dispenser trough and if she had permission to eat concentrate. Each entrance to the concentrate feeding stations produced a data log containing cow identification, time of entrance, total feeding time, and weight of delivered feed. All water bowls in the barn were equipped with antennas for cow identification and water flow registration (Bio-control A/S). Each visit to a water bowl produced a data log consisting of cow identification, time of visit, total drinking time, and amount of water consumed. The shortest interval that could be recorded was 1 s. Time of passage and redirection in control gates were recorded together with cow identity. Data related to milking was electronically registered in the AM system. Data from roughage feeding stations, concentrate feeding stations, water bowls, control gates, and the milking unit were trans-

Figure 2. The relative frequency distribution of observed intervals between feeding visits (a) and drinking visits (b), presented with class widths of 10 min. The chosen y-axis resulted in the first classes not being shown; these were 78.0% (a) and 58.4%, 8.2%, and 5.2% (b). The figure represents pooled data for all cows.

ferred automatically to a database for storage and analysis.

Data Handling and Statistical Analysis

Visit analysis in mixed distribution models. A feeding visit was a visit to either a roughage or a concentrate station. Feeding intervals were LN-transformed, and mixtures of Gaussian (Normal) and Weibull distributions –(G-G, G-W, G-G-G, and G-G-W) were fitted to individual data. For individual feeding data, both 2-population and 3-population models were fitted. For individual drinking data, only 3-population models were fitted. The estimation of model parameters was handled by the maximum likelihood method described by Everitt and Dunn (2001), and a program for the iterative process was written in the IML procedure. All statistical models and procedures referred to in this study were handled by SAS 8.02 (SAS, 1999). A likelihood ratio test using the approximation χ^2_3 distribution was performed to test the need of a third population in addition to a mixture of 2 populations. For models with equal numbers of populations, the test does not allow for different types of distributions, such as G-G vs. G-W. In these cases, log likelihood values were simply compared without any statistical testing. Distributions in the models were denoted as $i = 1$ to 3, where $i = 1$ was the distribution with the lowest mean interval. For each normal population, the mean μ_i , the variance σ_i^2 , and the proportion parameter p_i were estimated. Because of the condition $\sum p_i = 1$ for the proportion parameter, the number of estimated p_i was 1 or 2 for the 2- and 3-population models, respectively. The mean (given in original time) of the Normal distribution was trans-

formed from the estimated model parameters as $e^{\mu + \sigma^2/2}$ (Johnson, 2000). For models including a Weibull distribution, the scale parameter (α) and the shape parameter (β) were estimated. From these 2 parameters, the expectation (μ_i) was derived as $\alpha \Gamma(1 + 1/\beta)$ (Johnson, 2000), where Γ denotes the gamma function. The mean (given in original time) of the Weibull distribution was transformed from the estimated model parameters according to Appendix A. The definitions of the meal and bout criteria were points where 2-population curves intersected. Probability density functions of 2-population and 3-population models were compared with frequency distributions presented in bar charts, with bar widths of 0.5 LN units. The following general linear model was used to reveal differences of individual parameter estimates and meal and bout criteria between groups of cows:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \quad [1]$$

where y_{ijk} = parameter estimate or meal and bout criteria of milking frequency group i , cow age group j , and cow number k ; μ = overall mean; α_i = effect of milking frequency group i (HF or LF); β_j = effect of cow parity j (primiparous or multiparous); and ε_{ijk} = random error. Interactions were included in the model if significant.

Individual meal and bout criteria were used to calculate least squares means for the daily number of feeding meals and those for the daily number of drinking bouts. The start of a meal or a bout was determined to be the visit that defined a separate meal or a separate bout (i.e., elapsed time since the last visit was longer than the meal or bout criteria, respectively). The end of a meal or a bout was determined to be the last visit that,

by definition, belonged to that meal or that bout. Duration of a meal was calculated as the elapsed time between the start and end of a meal. When a cow approached one of the 2 control gates, the gate could either open to let the cow pass through, which was registered as a gate passage, or it could remain closed, which was registered as a gate redirection. The elapsed time from a gate redirection to a registration in the milking unit is referred to as redirection time. The probability of starting a meal within 15 min at a certain time since last meal (z) was calculated as the number of intervals during $z + 15$ divided by the number of intervals after time point z . Predicted starting probabilities were calculated from model estimates.

Individuality in feeding and drinking patterns.

The total random variation (σ^2_{error}) in parameter estimates was separated into 2 parts: variation between individual cows ($\sigma^2_{\text{between}}$) and variation within individual cows (σ^2_{within}). This division of the variance corresponds to what can be done when the μ_i parameters are estimated directly by the usual means within and between cows (e.g., when samples are taken from ordinary normal nonmixture distributions). Total random variation in individual parameter estimates of the mixed distribution models was obtained as the mean square of the random error term in the univariate version of model 1. Variation within cows was assumed to be equal for all individuals and was obtained as the means of the squared standard errors of individual parameter estimates of mixed distribution models. For each parameter estimate, variation between individual cows could then be calculated as the difference between total random variation and variation within cows ($\sigma^2_{\text{between}} = \sigma^2_{\text{error}} - \sigma^2_{\text{within}}$). Using the standard errors of the estimated variance components, the variation between cows was then tested for difference from zero by a test statistic following approximately the standard $N(0,1)$ -distribution.

RESULTS

Appropriate Models for Feeding and Drinking Visit Analysis

During the experiment, a total of 83,249 feeding intervals were extracted from the database. Figure 2a shows the frequency distribution of observed feeding intervals. The distribution did not decline continuously; rather, it reached a nadir between 50 and 100 min, after which the frequencies increased again. Further, it showed an excess of very short intervals, which calls for an analysis on logarithmic data. Figure 3a showed the existence of 2 distinct populations of feeding intervals. The larger of the 2 showed some nonnormality with more observations on the right side and less on

the left side of an imagined fitted normality curve. Explanation for this nonnormality was mainly in the distribution of intervals including at least 1 visit to water bowls (concentrates/roughage $\rightarrow$ water bowl $\rightarrow$ concentrates/roughage; Figure 3d). The left population in Figure 3d was placed at a position along the x-axis where it caused the nonnormality of the distribution in Figure 3a. Intervals including visits to water bowls were responsible for more than one-third of all recorded feeding intervals that gave them the potential to affect greatly the shape of this distribution. Distribution of intervals ending with concentrates (roughage/concentrates $\rightarrow$ concentrates; Figure 3c) had a similar shape to the distribution including all intervals, which makes these intervals responsible for some of the nonnormality in the left population of the distribution including all intervals. In Figure 3b, the intervals between visits to roughage stations (roughage $\rightarrow$ roughage) were extracted. Except for the small right-hand tail, this distribution had a shape not far from normality. Its position on the x-axis revealed that it was responsible for the main part of the observations in the left population of the distribution that included all observations.

In total, 67,525 drinking intervals were extracted from the database. Figure 2b shows the frequency distribution of observed drinking intervals. As for feeding data (Figure 2a), an excess of very short intervals existed. Distribution showed discontinuity in its decline but not a distinct nadir as for feeding intervals. However, when plotted for individual cows, a more obvious and sometimes marked nadir appeared (not shown). Figure 4a shows a distribution with 3 peaks, each representing a population with the median values at different positions along the x-axis. The 3 populations that were extracted represented 64,405 of all observations. The first population from the left represented short intervals between drinking visits (water $\rightarrow$ water; Figure 4b). The second from the left of the 3 populations mainly corresponded to intervals including at least one feeding visit (water $\rightarrow$ roughage/concentrates $\rightarrow$ water; Figure 4c). The third population represented intervals that included a registration in either the control gate or milking unit (water $\rightarrow$ control gate/milking unit $\rightarrow$ water; Figure 4d).

Modeling Feeding Intervals for Individual Data

Both 2-population models converged easily for all cows. Clear evidence of the existence of a third population was found for 16 cows. The distribution of observed intervals showed a skewed first population and both the G-G-G and the G-G-W models converged to significant solutions ($P < 0.05$). Of these 16 cows, 9 were in their first lactation, and 7 were older cows. A moderate evi-

Figure 3. All feeding intervals recorded in roughage and concentrate stations ($n = 83,249$) (a); intervals ending in roughage stations (roughage/concentrates $\rightarrow$ roughage; $n = 43,710$) (b); intervals ending in concentrate stations (roughage/concentrates $\rightarrow$ concentrates; $n = 9950$) (c); and intervals including visits to water bowls (roughage/concentrates $\rightarrow$ water $\rightarrow$ roughage/concentrates; $n = 29,589$) (d). LN = natural logarithm.

dence of a third population was found for 4 of the cows; the distribution of observed intervals showed some skewness, but only one of the 2 models for 3 population converged to a significant solution. The remaining 10 cows showed no evidence of a third population. Figure 5a shows an example of 2-population models fitted to an individual distribution. This distribution is representative for distributions in which 3-population models could not be fitted significantly, which was a consequence of the relatively small right-hand skewness of the first population. The fit of the G-W model was somewhat better than the G-G model (log likelihood value was larger) in 20 of the individual data sets. Distributions where a third population was found are illustrated in Figure 5(b and c). Because of the right-hand skewness of the first population, the 2-population model fitted the data poorly. These distributions were better

described in 3-population models that resulted in a significant increase in fit. In 13 of the 16 distributions having clear evidence of a third distribution, the G-G-W model converged with larger log-likelihood values than the G-G-G model, indicating a better fit of the G-G-W model.

Means and standard deviations of estimated parameters from significantly fitted models are presented in Table 1. Means of intervals between meals ranged from 211 to 233 min for the different models. Inclusion of a Weibull distribution for the last population resulted in shorter meal criteria. The confidence interval was only between 3.1 and 7.0% of the meal criteria of the different models. Use of a 3-population model instead of a 2-population model had little effect on the measured feeding behavior for cows having clear evidence of 3 populations in their distribution (Table 2). When a Wei-

Figure 4. All intervals between drinking visits ($n = 67,525$) (a); intervals between drinking visits not including feeding or registrations in milking units or control gates (water $\rightarrow$ water; $n = 35,775$) (b); intervals between drinking visits including feeding, but not registrations in milking units or control gates (water $\rightarrow$ roughage/concentrates $\rightarrow$ water; $n = 11,881$) (c); and intervals between drinking visits including a registration in the milking unit or the control gates (water $\rightarrow$ control gates/milking unit $\rightarrow$ water; $n = 16,749$) (d). LN = natural logarithm.

bull distribution was used for the last population, meal criteria decreased slightly, and feeding behavior measurements were affected to some extent. The observed starting probabilities showed a consistent increase after 60 min. The predicted starting probabilities of all 4 models reflected the observed starting probabilities well up to approximately 180 min. After that, the G-G and the G-G-G models deviated from the observed values and predicted decreasing starting probabilities when the time since last meal increased (Figure 6).

Modeling Drinking Intervals for Individual Data

Two cows showed frequency distributions with only 2 distinct populations, and the 3-population models did not converge. Frequency distributions for the remaining 28 cows showed clear evidence of 3 popula-

tions, and both the G-G-G and the G-G-W models converged. For these cows, the log likelihood of the G-G-G model was always greater than that of the G-G-W model, which indicated a better fit when describing the third population as a Gaussian distribution. The observed distributions were very different between individual cows, and 4 of them are shown in Figure 7. In Figure 7a, the distribution shows 3 distinct populations that all seem to be fairly normally distributed. The overlap between fitted Gaussian distributions was small, and the bout criterion for this cow was estimated with a confidence interval of 4.2% of the criterion. The 3 populations in Figure 7d were indistinct, which resulted in a large overlap between fitted distributions. It also resulted in a confidence interval of 6.4% of the bout criterion. The distribution in Figure 7b had only 2 distinct populations, and a smaller population in be-

Figure 5. Functions of natural logarithmic (LN)-transformed feeding visit intervals representing the sum of 2 or 3 distributions (thick line) and separate densities (thin lines). Frequency distributions are also presented in bar charts with bar widths of 0.5 LN units. The 2 figure boxes in (a) represent data from an individual cow modeled in a Gaussian (G)-G and a G-Weibull (W) mixture, respectively. The 2 figure boxes in (b) represent data from an individual cow modeled in a G-G and a G-G-G mixture, respectively. The 2 figure boxes in (c) represent data from an individual cow modeled in a G-W and a G-G-W mixture, respectively. Number of observations: a) 2803, b) 3928, and c) 2852.

Table 1. Estimated distribution means (μ_i), proportional parameters (P_i), and meal criteria (MC) of different mixture models fitted to the natural logarithm (LN) of individual feeding and drinking intervals. Models were mixtures of Gaussian (G) and Weibull (W) distributions.

Item	Feeding model				Drinking model	
	G-G	G-W	G-G-G	G-G-W	G-G-G	G-G-W
Cows, no.	30	30	17	17	28	28
	Mean (SD)					
P first distribution	0.85 (0.03)	0.84 (0.04)	0.50 (0.14)	0.51 (0.17)	0.41 (0.10)	0.41 (0.10)
P last distribution	0.15 (0.03)	0.16 (0.04)	0.15 (0.05)	0.16 (0.03)	0.23 (0.10)	0.23 (0.10)
μ_1, s^1	4.60 (0.21)	4.57 (0.20)	3.86 (0.22)	3.93 (0.26)	3.34 (0.30)	3.34 (0.34)
μ_2, s^1	9.28 (0.47)	9.24 (0.33)	5.65 (0.32)	5.77 (0.36)	7.12 (0.49)	7.17 (0.56)
μ_3, s^1			9.30 (0.30)	9.19 (0.32)	9.31 (0.31)	9.23 (0.32)
σ^2_1, s^1	1.67 (0.30)	1.60 (0.26)	0.95 (0.29)	0.88 (0.23)	0.99 (0.26)	1.04 (0.48)
σ^2_2, s^1	0.41 (0.31)	0.47 (0.15)	1.16 (0.67)	0.91 (0.67)	1.01 (0.56)	1.07 (0.55)
σ^2_3, s^1			0.32 (0.13)	0.51 (0.19)	0.23 (0.11)	0.33 (0.17)
$\mu_1, \min^2$	4.0 (1.5)	3.7 (1.1)	1.4 (0.5)	1.4 (0.6)	0.84 (0.4)	0.9 (1.0)
$\mu_2, \min^2$	233.3 (73.0)	219.1 (61.8)	9.1 (4.1)	8.3 (3.4)	39.12 (20.1)	38.9 (21.6)
$\mu_3, \min^2$			222.9 (61.9)	211.0 (54.6)	214.6 (58.6)	197.3 (68.1)
MC, $\min^3$	55.31 (18.8)	41.7 (13.1)	55.30 (23.2)	39.9 (18.7)	3.64 (1.5)	3.71 (2.1)
MC, CI ⁴	3.06 (0.08)	3.62 (0.04)	3.64 (0.02)	7.0 (0.08)	5.6 (0.08)	4.8 (0.02)

¹Natural logarithm in seconds for μ_i and natural logarithm in seconds squared for σ_i^2 .

² $\text{Exp}(\mu + \sigma^2/2)/60$ for normal distributions, for Weibull distributions see Appendix A.

³Exponent of natural logarithm transformation divided by 60.

⁴The 95% confidence interval (CI) (standard deviation $\times$ 1.96) expressed as a percentage of meal criteria.

tween was responsible for a small proportion of the total number of observations. There was no difference in measured drinking behavior when using the G-G-W model compared with the G-G-W model (Table 2).

Milking Frequency and Parity

Milking frequency had significant effects on several parameters estimated in the G-W model (Table 3). Cows in the HF treatment showed greater ($P < 0.05$) proportions of intervals in population 1, and a greater ($P < 0.05$) mean of intervals between meals and longer ($P < 0.05$) meal criteria. These effects were not significant for parameters estimated in the G-G-W model (Table 4). No significant effects were detected for parity. Multiparous cows had somewhat longer ($P < 0.05$) mean drinking intervals in population 1 when compared with primiparous cows (Table 5). No effects on drinking estimates were found for milking frequency. Redirection

time was the elapsed time from a redirection in control gates until a cow was registered in the milking unit. Average redirection time was 124 ± 71 min for HF cows and 73 ± 21 min for LF cows.

Individuality in Feeding and Drinking Patterns

Fixed effects of model 1 accounted for 5 to 25% of the variation (i.e., $R^2 = 5$ to 25%) in different parameters, leaving approximately 75 to 95% of the variation in the random error term. Variation between individual cows ($\sigma^2_{\text{between}}$) explained most of the random variation in the parameter estimates of the mixed distribution models. For parameters from the model of feeding data, $\sigma^2_{\text{between}}$ was >0.95 for all parameters, leaving a small part of the random variation to be explained by variation within cows (Table 6). The somewhat lower $\sigma^2_{\text{between}}$ for criteria of drinking meals than for criteria of feeding meals indicated greater uncertainty in estimating these

Table 2. Measurements reflecting the short-term feeding and drinking behavior when meal criteria estimated in different models were used. Models were mixtures of Gaussian (G) and Weibull (W) distributions.

Item	Feeding model				Drinking model	
	G-G	G-W	G-G-G	G-G-W	G-G-G	G-G-W
	Mean (SD)					
Cows, no.	17	17	17	17	28	28
Meal criteria	52.9 (14.1)	40.5 (9.6)	52.8 (20.0)	39.9 (18.7)	3.7 (1.6)	3.7 (2.1)
Meals per day	5.5 (2.0)	5.7 (2.2)	5.4 (2.1)	5.7 (2.3)	14.5 (6.7)	14.5 (6.7)
Meal length	45.7 (32.7)	42.9 (31.1)	45.5 (32.7)	42.0 (30.9)	2.1 (1.8)	2.1 (1.9)
Visits per meal	6.47 (4.1)	6.2 (4.0)	6.6 (4.2)	6.2 (4.0)	1.9 (1.3)	1.9 (1.3)

Table 3. Estimated distribution means (μ_i), proportion parameters (P_i), and meal criteria (MC) of a mixture of one Gaussian distribution and one Weibull distribution fitted to the natural logarithm of individual feeding visit intervals. Estimates are presented as least squares means for high-milking frequency (6×/d), low-milking frequency (3×/d), and cows in first lactation and later lactation.

Parameter	Milking frequency		Lactation number	
	High	Low	First	Multiple
Cows, no.	15	15	10	20
	Mean (SE)			
P_1	0.86 ^a (0.01)	0.83 ^b (0.01)	0.84 (0.01)	0.84 (0.01)
P_2	0.14 ^a (0.01)	0.17 ^b (0.01)	0.15 (0.01)	0.16 (0.01)
μ_1, s^1	4.56 (0.05)	4.60 (0.05)	4.63 (0.06)	4.53 (0.04)
μ_2, s^1	9.42 (0.08)	9.04 (0.08)	9.20 (0.09)	9.27 (0.06)
$\mu_1, \min^2$	3.75 (0.29)	3.93 (0.29)	4.23 (0.33)	3.46 (0.24)
$\mu_2, \min^2$	254.7 ^a (14.9)	184.3 ^b (14.9)	220.7 (17.3)	218.3 (12.2)
MC, $\min^3$	48.0 ^a (3.4)	36.6 ^b (3.4)	44.1 (3.90)	40.5 (2.76)

^{a,b}Means within milking frequency having different superscript letters differ ($P < 0.05$).

¹Natural logarithm in seconds.

² $\text{Exp}(\mu + \sigma^2/2)/60$ for normal distributions; for Weibull distributions, see Appendix A.

³Exponent of natural logarithm transformation divided by 60.

criteria for the individual cows (Table 6). In all cases, however, $\sigma^2_{\text{between}}$ was >0.80 for parameters from the drinking model.

DISCUSSION

Satiety Concept and Feeding and Drinking Patterns

The satiety concept predicts that the probability of an animal starting a meal depends on the time since the end of the last meal (Metz, 1975). Based on this concept, Tolkamp et al. (1998) modeled the frequency distribution of LN-transformed feeding intervals and obtained meaningful meal criteria for dairy cows kept in loose housing with conventional milking. The frequency

distribution in Figure 1a shows a similar shape to published frequency distributions in dairy cows (Tolkamp and Kyriazakis, 1999). After a rapid initial decline in frequencies, there is a nadir in frequencies around 60 min, followed by a rise to a peak around 100 to 120 min, and then a continual decline to very low frequencies. This pattern indicates that onset of a meal is not a totally random process; instead, it is dependent on satiety. We could find no evidence in the literature that the frequency distribution of between-drinking intervals had been studied in an analogous way. Figure 2a shows the frequency distribution of between-drinking intervals. It shows the same rapid initial decline as observed for between-feeding intervals, but no distinct

Table 4. Estimated distribution means (μ_i), proportion parameters (P_i), and meal criteria (MC) of a mixture of two normal distributions and one Weibull distribution fitted to the natural logarithm of individual feeding visit intervals. Estimates are presented as least squares means for high-milking frequency (6×/d), low-milking frequency (3×/d), and cows in first lactation and later lactation.

Parameter	Milking frequency		Lactation number	
	High	Low	First	Multiple
Cows, no.	8	8	9	7
	Mean (SE)			
P_1	0.43 (0.07)	0.52 (0.05)	0.52 (0.06)	0.44 (0.07)
P_3	0.15 (0.02)	0.17 (0.02)	0.16 (0.01)	0.17 (0.01)
μ_1, s^1	3.98 (0.11)	3.90 (0.08)	3.89 (0.09)	3.99 (0.11)
μ_2, s^1	5.80 (0.17)	5.75 (0.12)	5.82 (0.13)	5.74 (0.16)
μ_3, s^1	9.33 (0.13)	9.09 (0.09)	9.20 (0.10)	9.22 (0.12)
$\mu_1, \min^2$	1.2 (0.2)	1.4 (0.2)	1.3 (0.2)	1.4 (0.2)
$\mu_2, \min^2$	8.3 (1.6)	8.4 (1.1)	8.9 (1.2)	7.8 (1.5)
$\mu_3, \min^2$	234.9 (20.5)	191.0 (14.4)	218.7 (15.9)	207.2 (19.4)
MC, $\min^3$	49.2 (8.3)	36.4 (5.8)	41.1 (6.4)	44.6 (7.8)

¹Natural logarithm in seconds.

² $\text{Exp}(\mu + \sigma^2/2)/60$ for normal distributions; for Weibull distributions, see Appendix A.

³Exponent of natural logarithm transformation divided by 60.

Table 5. Estimated distribution means (μ_i), proportion parameters (P_i), and meal criteria (MC) of a mixture of three normal distributions fitted to the natural logarithm of individual drinking visit intervals. Estimates are presented as least squares means for high-milking frequency (6×/d), low-milking frequency (3×/d), and cows in first lactation and later lactation.

Parameter	Milking frequency		Lactation number	
	High	Low	First	Multiple
Cows, no.	13	15	10	18
	Mean (SE)			
P_1	0.39 (0.03)	0.40 (0.03)	0.35 ^a (0.03)	0.43 ^b (0.02)
P_3	0.40 (0.03)	0.33 (0.03)	0.37 (0.03)	0.36 (0.02)
μ_1 , s ¹	3.44 (0.08)	3.35 (0.07)	3.55 ^a (0.09)	3.24 ^b (0.06)
μ_2 , s ¹	7.18 (0.14)	7.14 (0.13)	7.30 (0.15)	7.01 (0.11)
μ_3 , s ¹	9.36 (0.09)	9.28 (0.09)	9.35 (0.10)	9.29 (0.07)
μ_1 , min ²	1.0 (0.1)	0.8 (0.1)	1.0 ^a (0.1)	0.73 ^b (0.1)
μ_2 , min ²	40.0 (5.8)	40.6 (5.7)	43.9 (6.6)	36.7 (4.8)
μ_3 , min ²	222.8 (17.1)	210.7 (16.8)	223.1 (19.4)	210.4 (14.1)
MC, min ³	3.7 (0.4)	3.9 (0.4)	4.29 (0.5)	3.28 (0.34)

^{a,b}Means within either milking frequency or lactation number having different superscript letters differ ($P < 0.05$).

¹Natural logarithm in seconds.

² $\text{Exp}(\mu + \sigma^2/2)/60$ for normal distributions; for Weibull distributions, see Appendix A.

³Exponent of natural logarithm-transformation divided by 60.

nadir at 60 min was detected. In contrast, the plot shows a discontinuity at this time point. However, pooling of data is partly responsible for this effect, and for some individuals, a distinct nadir actually occurred at about 60 min. As for feeding intervals, there seems to be a shortage of intervals with durations of about 60 min, indicating that drinking visits are not randomly distributed in time.

Finding the Appropriate Models

The relative frequency of LN-transformed intervals presented in Figure 3a showed 2 distinct populations of intervals. The larger of the 2 was skewed to the right (i.e., it had more observations to the right and fewer to the left of an imagined fitted normality curve). Tolkamp and Kyriazakis (1999) identified a third cluster of intervals that separated the within-meal intervals into 2 distributions. This distribution was explained to be the

result of feeding intervals in which drinking was included. The finding in our study that intervals including drinking comprised more than one-third of all feeding intervals, together with their position on the x-axis, confirms that cows visit the water bowls and feeding stations indiscriminately during a meal. This makes intervals including drinking the cause for the skewness in the larger of the 2 feeding-interval populations. From the obvious increase in fit when adding a third population to the model (Figure 5, b and c), it was preferable to model the feeding intervals in a mixture of 3 distributions for some of the individuals. The finding that 9 of 10 first-lactation cows had clear evidence of a third population may suggest that their social environment has an influence on the feeding pattern. Socially low-ranked cows have been found to have subordinate access to feed troughs (Olofsson, 2000), which might have forced the cows in this study to interrupt their feeding for prolonged periods during a meal. The intervals ending in the concentrate stations were distributed along the whole x-axis (Figure 3c), and the first population in this distribution is like the distribution of all intervals (somewhat skewed to the right). This is likely an effect of cows being obliged to wait in front of the concentrate feeding station when it is occupied. Because the effects on measurements reflecting feeding patterns turned out to be small (Table 2), the addition of a third population to the model may be of limited importance. However, the 3-population model contributes to the explanation of the skewness of population 1 and provides a better understanding of the feeding visit patterns.

Table 6. Proportion of the total random variation of estimated distribution means (μ_i), proportion parameters (P_i), and meal criteria that was explained by variation between individual cows. Calculations based on individual fittings of a Gaussian-Weibull model (G-W) for feeding data and a triple-Gaussian model (G-G-G) model for drinking data.

Parameter	Feeding	Drinking
P_1	0.95	0.84
P_2	0.95	0.87
μ_1	0.98	0.93
μ_2	0.98	0.88
μ_3	—	0.93
Meal criteria	0.95	0.86

Figure 6. a) Probability of cows starting a meal during the next 15 min relative to the time since last meal. Feeding intervals ($n = 83,249$) were pooled for all 30 cows having starting probabilities as observed (plus), as predicted by the Gaussian-Weibull (G-W) model (solid line) and as predicted by the G-G model (broken line). b) Feeding intervals ($n = 45,194$) were pooled for the 16 cows that needed 3 populations with starting probabilities as observed (plus), as predicted by the G-G-W model (solid line) and as predicted by the G-G-G model (broken line). For clarity, data points <60 min are not shown.

According to the concept of satiety, the probability of a cow starting a meal should increase with the time since last feeding. Yeates et al. (2001) found that a G-G-G model predicted decreasing starting probabilities, which was in contrast to what would be expected. When they instead fitted a G-G-W mixture to the same data, they achieved a model that predicted increasing starting probabilities. In the present study, we found that inclusion of a Weibull better predicted starting probabilities and better predicted that the statistical fit increased for most cows. Estimated meal criteria were shorter for both the Weibull models compared with models having Gaussian only. With the increase in fit and the better agreement with biological theories, this estimation of meal criteria is probably closer to reality.

By studying the distribution of all drinking intervals (Figure 4a), it seems appropriate to model the feeding intervals in a mixture of 3 distributions. However, 2 cows deviated from this general pattern and were found to have only 2 populations of intervals. The G-G-G model fitted the data better than the G-G-W model for all individual cows. Confidence intervals of bout criteria were generally greater than those associated with feeding data (Table 1), indicating greater uncertainty in the estimated model parameters of the drinking model. The overlap between distributions was also greater compared with feeding data, which increases the risk of wrongly assigned observations (Figure 7). Dado and Allen (1993) analyzed automatically obtained interdrinking intervals for cows in tie stalls and presented them in a log-survivorship curve. They estimated the bout criteria to be about 4 min, which is close to the bout criteria that we estimated in our study. In contrast

to what was found for feeding data, few significant effects on parameter estimates were detected for drinking intervals. The explanation for this could be that water bowls were placed in both the waiting and the feeding areas, which made water more accessible than feed. The first population of drinking intervals corresponds to short interruptions (<1 min) in drinking for various reasons, and the second population includes visits to feeding stations. This mix of feeding and drinking activities could be found for 28 of the 30 cows in the present study. The third distribution of drinking intervals (Figure 4d) had a mean interval length that was close to the mean interval length of between-meal intervals of feeding. We could show that during the intervals of the third population, the cows had spent some time outside the feeding area. Intervals of this population are the result of drinking visits coinciding with the start of a feeding meal. It is likely that this population reflects the periods of idling, resting, and rumination. Halachmi et al. (2000) presented plots that reflected the sequential activities of 3 individual cows. For these cows, drinking bouts and feeding meals most often coincided. The G-G-G model was statistically better than the G-G-W model for all individuals in our study. However, we do not argue that this is the ultimate model. More work in this area could increase understanding of the biological background to the observed drinking patterns.

Cow Age and Frequency Group

Based on the calculated confidence interval, meal criteria for feeding could be estimated with a low uncer-

Figure 7. Functions of natural logarithmic (LN)-transformed drinking visit intervals representing the sum of 2 or 3 distributions (thick line) and separate densities (thin lines). Frequency distributions are also presented in bar charts with bar widths of 0.5 LN units. Each figure box (a, b, c, and d) represents data from individual cows modeled in a Gaussian (G)-G-G mixture. Number of observations: a) 2906, b) 1295, c) 1328, and d) 3217.

tainty. In this study, average individual meal criteria for HF were somewhat higher than published meal criteria estimated in different kinds of mixed models; Tolcamp et al. (1998) estimated meal criteria in a mixture of 2 Gaussian distributions and estimated 42 min; Yeates et al. (2001) found that a mixture of 2 Gaussian distributions and one Weibull distribution best described their data and estimated meal criteria to 29 min; Tolcamp et al. (2002) estimated meal criteria in a mixture of 2 Gaussian distributions and one Weibull distribution to range between 24 and 28 min for different groups of cows. These 3 studies were all conducted on dairy cows in loose housing with free access to roughage. We calculated redirection time to describe the cows' motivation and ability to enter the milking unit after a redirection in control gates. Redirection time turned out to be of considerable duration (average = 124 ± 71 min for HF), which delayed their return to the feeding

areas. Cows in the HF treatment had, on average, longer redirection times than LF, and, as a result, both means of intervals between meals and meal criteria were greater for HF than for LF. Earlier studies of feeding patterns in AM systems have used definitions of meals that have either been arbitrary or based on the assumption that meals are randomly distributed in time, resulting in meal criteria as short as 13 min (Morita et al., 1996) and 10 min (Harms et al., 2002). The relatively long-meal criteria estimated in our study were concluded to be the result of the redirection time, which in turn was a consequence of the controlled cow traffic. Increased understanding of feeding and drinking patterns of dairy cows, and the impact of different cow traffic systems on these patterns, are important in the development of individual cow management strategies in AM systems. In addition, this knowledge could

be used in computer simulations for evaluating new AM system designs, as discussed by Halachmi et al. (2000).

Individuality in Feeding and Drinking Patterns

Ketelaar-deLauwere et al. (1998) noticed individual differences in how cows used the selection unit in an AM system. Hopster and Blokhuis (1994) found that cows responded to a social stressor in a way that was characteristic for each individual. The fact that individual cows exhibit different reactions to the same situation indicates that management changes made on the group level are an inefficient management strategy. Only some of the cows in the group can be expected to react according to plan in such management. In our study, the major part of the variation in feeding and drinking patterns was due to differences between individual cows, whereas differences within individuals explained a smaller part of the variation. This suggests that cows develop feeding and drinking patterns in the AM system that are characteristic for each individual and are consistent over time. Hopster et al. (1998) studied the side preference of cows in a 2-sided milking parlor and found that side preference was stable over a prolonged period of time. Further, Schrader (2002) found that spontaneous behavior, such as duration of lying time and overall activity, was consistent over time for individual cows. The consistency over time of cow behavior increases the possibility of using feeding and drinking patterns as input information in an individual management system.

CONCLUSIONS

Modeling feeding intervals in a mixture of Normal and Weibull distributions gave estimations of meal criteria having small confidence intervals. Similar to feeding, drinking is not a random process, and mixture distribution models are also applicable for drinking data. Because of differences in meal criteria caused by the cow traffic system, arbitrarily chosen meal criteria are likely to be misleading in studies of feeding and drinking behavior. When treatment effects on meal criteria can be expected, meal criteria should be estimated on an individual basis. The inclusion of a Weibull distribution for the population of intervals between meals increased the statistical fit and predicted biologically relevant starting probabilities and estimated meal criteria that were closer to what was published by others. The existence of a third population with intervals including drinking is highly individual, and as a consequence, both 2-population models and 3-population models must be considered when fitting models on an individual basis. However, only small changes in the

estimations of meal criteria can be expected when adding a third population to the model. Three-population models seem to be appropriate for modeling drinking visit intervals for most cows. To judge from the confidence intervals, bout criteria with low uncertainty were estimated. Inclusion of a Weibull distribution did not increase the fit of the drinking model, and further studies should evaluate the appropriateness of other distributions than Gaussians to describe populations 1 and 2. Because of the finding that most variation in feeding and drinking patterns can be explained by differences between and not within individual cows, it can be concluded that cows develop feeding and drinking patterns that are characteristic for the individual cow and consistent over time. Based on this observation, cow activities such as feeding and drinking patterns, likely have the potential to be input information for such purposes as monitoring and decision making in individual control management systems.

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APPENDIX A

Denoting the natural logarithmic (LN)-transformed time by Y , the expected value of the original time is found by integrating the product of e^y and the Weibull density function. By the transformation $t = (y/\alpha)^\beta$, the integral can be rewritten according to

$$\int_0^\infty e^{y\frac{\beta}{\alpha}} \left(\frac{y}{\alpha}\right)^{\beta-1} e^{-(y/\alpha)^\beta} dy = \int_0^\infty e^{\alpha t^{1/\beta}} e^{-t} dt.$$

As this integral cannot be evaluated explicitly, $e^{\alpha t^{1/\beta}}$ is expanded into a series, so that the expectation of e^Y is obtained as $\int_0^\infty \sum_{j=0}^\infty \frac{(\alpha t^{1/\beta})^j}{j!} e^{-t} dt = \sum_{j=0}^\infty \alpha^j \frac{\Gamma(1 + j/\beta)}{\Gamma(1 + j)}$, where Γ denotes the gamma function whose numerical evaluation can be performed by the IML procedure in SAS. In this application, the sum can be truncated after the first 100 terms.