Water Intake and Dry Matter Intake Changes as a Feeding Management Tool and Indicator of Health and Estrus Status in Dairy Cows

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ABSTRACT

This study investigates whether dry matter (DM) or water intake is affected by the presence of disease or estrus in dairy cows and whether water intake can serve as an accurate substitute for monitoring changes in DM intake (DMI). A combined cumulative sum (CUSUM) and Shewhart monitoring scheme is proposed to detect DMI changes and emerging disease or estrus. Daily readings from 35 inline water meters for 35 water cups in a tie-stall barn at the University of Minnesota were collected from September 2005 until June 2006. Two cows were assigned to each water cup. Individual DMI were recorded for each of the 70 cows on the study. All drug or hoof treatments administered to the cows along with breeding and calving events were also recorded and classified as 1 of the following 6 event categories: estrus, calving, mastitis, fever, hoof treatment, and other. Analysis of covariance was used to identify factors significantly changing intake. Only the first 150 d in milk (DIM) were considered in the analysis. Six event categories plus DIM, ambient temperature, relative humidity, and parity were entered as independents into the model. Calving, primiparity, and health events categorized as “other” were associated with decreased DM and water intake. Mastitis decreased DMI and fever negatively affected water intake. Both intakes increased with DIM, and water intake decreased with increase in humidity. Covariance analysis was used to investigate the relationship between DMI and water intake. In model 1, analysis was done for a pair of cows, whereas model 2 modeled DMI of the whole group of 70 cows. Water intake, ambient temperature, humidity, and DIM were entered as independents in both models and parity was entered in model 1. Polynomial models and 2-way interactions were also considered. Water intake, ambient temperature, DIM, and DIM² were kept in final models 1 and 2, and parity was kept in model 1. Final models for cow pairs and a group of 70 cows resulted in R² of 0.50 and 0.82, respectively. The

proposed CUSUM-Shewhart DMI monitoring scheme successfully detected emerging disease even in the first week of lactation. Monitoring water intake can serve as an alternative to measurements of DMI for groups of cows and has the potential of predicting change in individual cow health and estrus status.

Key words: disease detection, dry matter intake, water intake

INTRODUCTION

Multiple researchers have identified a negative effect of various health disorders on DMI in dairy cows. An extensive study of more than 1,000 lactations (Bareille et al., 2003) demonstrated a negative association between reproductive (difficult calvings, retained placenta, metritis), metabolic (ketosis, milk fever), and udder-related (edema, teat injury, local and systemic mastitis) problems and DMI. Enteritis, decreased rumen motility, left displaced abomasums, (Ostergaard and Grohn, 2000), and acidosis (Owens et al., 1998; Oetzel, 2004) have also been associated with changes in DMI. It has been reported that DMI is not only associated with but in many cases precedes clinical manifestation of disease. A study of periparturient dairy cows (Zamet et al., 1979) demonstrated a significantly greater decrease in voluntary feed intake up to 3 wk before calving in cows diagnosed with mastitis, metritis, retained fetal membranes, fat cow syndrome, paresis, or displaced abomasum postpartum compared with cows experiencing no health problems postcalving.

Concentrate intake (Mol et al., 2001) and feed intake (Oetzel, 2004) have been identified as potential monitors helpful in early disease detection. In his article on diagnosis and treatment of fresh cow disorders, Guterbock (2004) states that screening for disease must be based on traits that can be measured in real time. Automated systems for monitoring feeding behavior exist (Growsafe, Growsafe Systems Ltd., Airdrie, Alberta, Canada; DeLaval feeding stations, DeLaval, Tumba, Sweden). Collection of feed intakes on commercial dairy farms currently, however, relies heavily on manual labor, making daily recording laborious and prone to

Received December 6, 2007.

Accepted May 16, 2008.

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human error. As a result, this valuable information on health and nutrition management of the dairy herd may often be unreliable or insufficiently available. An often-reported strong correlation between water and DM intakes (Holter and Urban, 1992; Dado and Allen, 1994; Beede, 2005) suggests the possibility of using water intake as an indirect way of monitoring DMI.

Most research on water consumption and utilization in dairy cattle focuses on its metabolism (Woodford et al., 1984; Murphy, 1992; Silanikove et al., 1997) and prediction of water intake (Holter and Urban, 1992; Meyer et al., 2004). Some studies have identified the potentially negative association of stray voltage and mineral composition on water intake (Beede, 2005). Little information is available, however, on the relationship between the health status and water consumption of dairy cattle. Meyer et al. (2004) report decreased intake due to estrus and health problems, whereas Cottee et al. (2004) observed an increase in intake of sodium bicarbonate supplemented water during experimentally induced acidosis.

Two recently published studies have emphasized the potential of monitoring DM or water intake to detect disease in swine and beef cattle. Quimby et al. (2001) used feeding behavior records to monitor health of feedlot steers. Madsen and Kristensen (2005) reported use of water intake of growing pigs for early disease detection. Both studies demonstrated a successful application of statistical process control (SPC) cumulative sum (CUSUM) charts in early detection of change in health status.

Statistical process control is a quality improvement tool that has been extensively used in nonagricultural industries in the past century. The statistical methods applied to control charts aim to distinguish (with a certain level of confidence) between common-cause variation resulting from usual day-to-day fluctuations in process output and variation resulting from special cause such as changes in the materials, people, machine, environment, or method in which the process was performed. This distinction is meant to aid in identifying when a true change has occurred and action is needed to ensure desired process performance. Type I and type II error rate in SPC expressed as average run length (ARL) and average time to signal are determined by the choice and design of the SPC chart. Shewhart charts are geared toward early detection of larger shifts (≥ 3 SD), whereas CUSUM charts can be designed to detect small, sustained drifts. When a change in health or reproductive status of a cow is associated with a small sustained or large change in DM or water intake, applying a combined CUSUM-Shewhart chart to monitor DMI might help in early disease or estrus diagnosis.

The present study investigates the relationship between DMI, water intake, and change in cow status. The aims of the study were to 1) evaluate the impact of disease or estrus on DM and water intake, 2) determine whether water intake can serve as a monitor of changes in DMI, and 3) explore the potential of a DMI and water intake monitoring scheme using CUSUM and Shewhart charts to detect change in cow health or reproductive status.

MATERIALS AND METHODS

Data

Dry matter and water intake was recorded daily for 35 pairs of dairy cows from September 2005 to June 2006. Cows were housed in a tie-stall dairy barn at the University of Minnesota St. Paul campus and represented different breeds (32 Holsteins, 38 crossbreds between Holstein, Jersey, and Montbeliarde) and lactations (28 primiparous and 42 multiparous). Cows were fed a TMR according to the NRC (2001) recommendations and offered water *ad libitum*. A separation of the feed bunk between stalls allowed collection of DMI for individual cows. Water intake was collected daily through AMCO 5/8" Poly Direct Read (Elster AMCO Water Inc., Ocala, FL) inline water meters measuring the water flow from each water cup. The water meter manufacturer reports an accuracy of 99.6% at high flow. The observed accuracy of water meters installed in the St. Paul dairy barn at a simulated average cow drinking bout size of 2 L was estimated at 95%. Two cows were assigned to each cup; therefore, water intake was measured as total intake for 2 cows. Cows were also offered water in the holding pen before each of the 2 milkings and at pasture during the grazing season (September and October 2005, and April, May, and June 2006). Water intake while away from the stall (~ 2.0 h on pasture during the grazing season and 30 min during each milking) was not accounted for. Daily water and DM intake data were collected for the first 150 d of lactation. All cows calved between September 2005 and February 2006. Cows were assigned to adjacent stalls according to calving dates to decrease the difference in DIM between cows drinking from the same water cup. The average difference in DIM between cows in the same water cup pair was 10.5 d (SE = 1.54). Parity was not controlled within cow pair and was considered as a separate factor in the statistical analysis.

All hoof treatments and drugs administered to the cows during the study period were recorded by date and cow ID in a barn logbook. It was assumed that animals in need of treatment and the type of treatment necessary were determined correctly by the herd man-

ager or veterinarian administering the treatment. Cow hoof and drug treatments were later assigned to one of the following health event categories: mastitis ($n = 57$), fever ($n = 4$), hoof treatment ($n = 44$), and other ($n = 11$). Category "other" included ketosis, milk fever, and antibiotic treatments. Subsequent health events from the same category and for the same animal had to be separated by at least 7 d to be considered a separate event. However, if an animal experienced an event from a different category, it was considered a separate event even if less than 7 d separated the 2 treatments. Cows were subject to synchronized breeding and all breeding dates were recorded by date and cow ID. Calving date and lactation number were also recorded for each cow. Six different event types were identified: 4 health event types (hoof, fever, mastitis, and other) and 2 reproductive events (calving and estrus). A 7-d event period was assigned to the 3 d before, the day of, and 3 d after each event.

Daily relative humidity (RH) and ambient temperature data for the study period were obtained from the St. Paul Downtown Airport weather station.

Analysis

DMI. The Proc MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) was used to analyze the associated effect of disease or estrus on the DMI of individual cows. Individual cow DMI was entered as the dependent variable, and parity and 6 event categories were entered as 7 fixed factors with 2 levels each. The 2 levels of the 6 event factors distinguished between days within the event period and days outside of the event period. The 2 levels of parity were 1 and >1 . Daily RH and ambient temperature were also entered into the model. Intercept and cow DIM were entered as random factors with cow specified as subject. Days in milk were also entered as a separate categorical variable with 1 level per each DIM and used in the repeated statement. The appropriate covariance structure was selected by comparing the covariance parameter estimates and model fit statistics between alternative models (Singer, 1998; Littell et al., 2000). Two-way interactions between DIM, parity, and 6 event factors were also included in the full model.

Water Intake. Analysis was performed similarly to the analysis of DMI data except that measurements represented an average per-cow intake of the 2 cows in the water cup pair rather than individual cow data. The Proc MIXED procedure of SAS was used (SAS Inst. Inc.). Water intake was entered as the dependent variable, and parity and 6 event categories were entered as 7 fixed factors with 2 levels each. The 2 levels of the 6 event factors distinguished between days within the

event period for either cow in the water cup pair and days outside the event period for both cows. Parity in the water intake model represented the average lactation of the 2 cows sharing the same water cup; the 2 levels of parity were 1 and >1 . Daily RH and ambient temperature were also entered into the model. Average DIM were calculated for each water cup pair and entered as random factors along with the intercept. Days in milk were also entered as a separate categorical variable with 1 level per each DIM and used in the REPEATED statement. The appropriate covariance structure was selected by comparing the covariance parameter estimates and model fit statistic between alternative models (Singer, 1998; Littell et al., 2000). Two-way interactions between DIM, parity, and 6 event factors were also included in the full model.

Relationship Between Water Intake and DMI. The Proc GLM procedure of SAS (SAS Inst. Inc.) was used to investigate the relationship between DMI and water intake. Two different models were analyzed. In model 1, average per-cow DMI, average per-cow water intake, and average DIM between the 2 cows in the same water cup pair, were calculated for each day of study for each water cup pair. In model 2, average per-cow DMI, average per-cow water intake, and average DIM for the whole study group (70 cows) were calculated for each day of study. The full models included DMI as the dependent variable, and water intake, RH, ambient temperature, DIM, and biologically meaningful 2-way interactions as the explanatory variables. Polynomial models were also investigated. In model 1, a class variable of average parity with 2 levels (1 and >1) was also entered into the model. The choice of variables in the final models was based on assessment of their impact on the model fit statistics.

Use of SPC Charts to Assess DMI Changes. To account for the autocorrelation and the drift in DMI as lactation progresses the following model including a first-order autoregressive factor and DIM was fit (Montgomery, 2005):

$$DMI_t = \zeta + \varphi DMI_{t-1} + \theta DIM_t + \varepsilon_t,$$

where DMI_t is cow DMI at day t , DMI_{t-1} is the DMI at day $t - 1$, DIM_t is the cow's day of lactation at day t , and ε_t is the residual term. Data from all the cows was used for the model estimation. To account for the effect of lactation stage and number on the slope of the DMI curve and to simplify the models, the first 21 DIM and the remaining 129 DIM, and cows and heifers were analyzed independently resulting in estimation of 4 separate models. Only significant terms ($P < 0.05$) were kept in the model. The estimated models were

then applied to individual cow data and residuals were plotted on separate CUSUM charts for each individual animal. All charts were plotted retrospectively and were not used to identify animals in need of treatment during the study period.

Designing a CUSUM chart requires choosing the size of shift in mean or standard deviation of interest and the rate of false alarms referred to in SPC as ARL. Once these two parameters are determined, the upper and lower control limits can be obtained using software provided by Hawkins and Olwell (1998; <http://www.stat.umn.edu/cusum/software.htm>). Any point plotted outside the upper or lower control limit on any of the charts is considered a sign of significant change in DMI. At the onset of lactation, no historic data were available to estimate the mean and variation in DMI necessary to establish the upper and lower limits for the charts. Therefore, a self-starting CUSUM approach was adopted (Hawkins and Olwell, 1998). The self-starting CUSUM starts at mean 0 and sigma 1 and updates the mean and sigma estimates with each data point. Upward (S^+) and downward (S^-) CUSUM for the self-starting chart for location are calculated as presented below (Hawkins and Olwell, 1998):

$$S_n^+ = \max(0, S_{n-1}^+ + U_n - k)$$

$$S_n^- = \max(0, S_{n-1}^- - U_n + k),$$

where $2 \times k$ is the shift in mean that the chart is optimized to detect, and U_n is the inverse normal of the Student's T distribution with parameters $F_{n-2}(a_n T_n)$:

$$a_n = \sqrt{\frac{n-1}{n}}, T_n = \frac{X_n - \bar{X}_{n-1}}{S_{n-1}}, S_n^2 = \frac{W_n}{n-1},$$

and $\bar{X}$ and W_n are the running mean and standard deviation, respectively, of the residuals.

The upward (V^+) and downward (V^-) CUSUM for the self-starting chart for scale are calculated as follows (Hawkins and Olwell, 1998):

$$V_n^+ = \max(0, V_{n-1}^+ + U_n^2 - r)$$

$$V_n^- = \max(0, V_{n-1}^- - U_n^2 + r),$$

where r is the reference value determined by the size of shift in variation that the CUSUM chart for scale is optimized to detect. The reference value was obtained from software provided by Hawkins and Olwell (1998; <http://www.stat.umn.edu/cusum/software.htm>).

The Shewhart chart is obtained by plotting the U_n values on a chart with a mean 0 and 3 and -3 upper and lower control limits. To prevent the presence of extreme values from distorting the mean and sigma estimates, winsorization was applied to all data (Hawkins and Olwell, 1998). This procedure reduces potential outliers to a value determined by the winsorizing constant. To enhance the ability of the CUSUM to detect changes in DMI at the onset of lactation, a fast initial response (FIR) approach was used (Montgomery, 2005). With this approach, the CUSUM at the onset of charting was set halfway between zero and the lower limit, sensitizing the chart to decreases in DMI at onset of lactation. To account for small, sustained changes in mean and variation in DMI as well as large changes to the mean, a CUSUM for location and scale and a Shewhart chart were plotted for each cow. The CUSUM were set to detect 1 sigma shift in mean and 1 sigma increase and 0.5 sigma decrease in variation, with an ARL of 500. When 70 cows are monitored every day, an ARL of 500 corresponds to an average of 0.98 false signals per week per chart type. The Shewhart chart has an ARL of 370, which corresponds to 1.32 false signals per week. Therefore, the scheme developed in this study would yield an average of 3.28 false signals per week out of the 1,470 points plotted and analyzed by the SPC charts. For detailed description of calculation of CUSUM, limits, ARL, winsorization, and the FIR approach, please refer to Hawkins and Olwell (1998).

RESULTS AND DISCUSSION

Association of Disease and Estrus with Intake

The majority of studies reporting changes in intake due to changes in cows' health or reproductive status focus on DMI. Metabolic (Owens et al., 1998; Ostergaard and Grohn, 2000; Oetzel, 2004), udder (Bareille et al., 2003), and reproductive (Sheldon, 2004; Huzzey et al., 2007) problems have all been associated with a decrease in feed intake. Decrease in intake has also been observed around parturition (Grummer et al., 2004). In our study, calving and health events categorized as "other" decreased both DMI and water intake ($P < 0.01$; Table 1). Lesser DMI was also associated with mastitis ($P = 0.013$), whereas decreased water intake was observed during days associated with fever ($P = 0.038$). Water intake tended to decrease when hoof treatment was administered ($P = 0.064$). Nishimori et al. (2006) also suggested a decreased DMI among cows in need of a hoof treatment.

Presence of estrus was associated with increased DMI ($P < 0.001$) and tended to have the opposite ef-

Table 1. Solutions for fixed effects included in the final DMI and water intake models¹

Fixed effect ²	DMI ³			Water intake ⁴		
	Estimate	SE	<i>P</i> -value	Estimate	SE	<i>P</i> -value
Intercept	19.03	0.702	<0.001	80.65	6.689	<0.001
DIM ⁵	0.03	0.003	<0.001	0.23	0.029	<0.001
Relative humidity	-1.25	0.186	<0.001	-8.39	1.431	<0.001
Parity (>1)	2.02	0.578	<0.001	14.96	6.561	0.029
Mastitis	-0.48	0.194	0.013			
Fever				-6.28	3.034	0.038
Hoof				-2.21	1.194	0.064
Other	-1.40	0.450	0.002	-11.77	2.641	<0.001
Estrus	0.61	0.122	<0.001	-1.13	0.633	0.075
Calving	-4.73	0.206	<0.001	-22.87	1.560	<0.001
DIM × parity (>1)				-0.09	0.037	0.017

¹Effects with no estimates, SE and *P*-values were eliminated from the final model.

²Only effects that remained in at least 1 of the 2 final models are included in the table.

³Mixed model of individual cows' DMI.

⁴Mixed model of average per-cow water intakes of 2 cows drinking from the same water cup.

⁵DIM represent the DIM of individual cow for DMI model and average DIM of 2 cows from the same water cup pair for the water intake model.

fect on water intake ($P = 0.075$). Observed decreases in water intake of cows in estrus have previously been reported (Meyer et al., 2004). The associated effect of estrus on feed intake reported by previous researchers, however, is either negative or insignificant. De Silva et al. (1981) did not report any changes in feed intake during the estrus period. Similarly to this study, a period of 3 d before to 3 d after estrus was considered. A decrease in time spent feeding has also been associated with estrus (Diskin and Sreenan, 2000). These findings stand in contrast with the 0.61-kg DMI increase observed in our study. Dry matter intake in our study was determined by subtracting the refusals from the amount of feed provided. It is possible that increased cow activity commonly associated with estrus resulted in some of the refusals being incorporated into bedding or spread outside the feeding area. This behavior might have resulted in underestimation of the refusals and subsequent overestimation of DMI. No measurements, however, were conducted to verify this possibility.

Lack of individual water intake measurement and no information on the water intake while cows were away from their stalls constitute two important confounding factors in our attempt to estimate the effect of disease or estrus on cows' water intake. Values reported in Table 1 might underestimate the actual magnitude of the effect of health or reproductive events on water intake. It is most likely that change in water intake observed for the cow pair can be contributed mainly to the cow experiencing a specific reproductive or health event. Because individual water intakes were not measured, the values reported in Table 1 indicate an average change in water intake within a cow pair when

at least 1 of the animals within the pair experienced a reproductive or health event. The reported per-cow change in daily water intake for the cow pair is therefore likely less than that actually manifested by the cow experiencing the status change.

More research is necessary to fully investigate the relationship between water intake and health problems. Results reported in our study, however, suggest that such a relationship exists and may provide a basis for cow health monitoring. Automated recording of water intake has been used to identify emerging diseases in swine production (Madsen and Kristensen, 2005) and resulted in detection of an outbreak of diarrhea 1 d before clinical signs were observed. Other researchers have found that monitoring feeding behavior in beef cattle can accelerate identification of morbid animals by 4 d (Quimby et al., 2001). Significant change in water intake associated with health problems observed for cow pairs in our study suggests that when individual water intakes are collected, similar sensitivity with greater specificity might be expected. Even if, however, water intake monitoring is limited to pairs of cows, the knowledge of which pair of cows might be experiencing health problems provides the herd manager with more information than not knowing about the change in drinking behavior at all.

Association of DIM and Parity with Intake

As expected, both water intake and DMI increased with DIM and were smaller for primiparous than for multiparous cows (Table 1). The negative sign of

the estimate for the DIM $\times$ parity (when parity >1), however, indicates that heifers' water intake changed at a greater rate. Although little is known about the differences in water intake between multiparous and primiparous cows, previous research suggests that older cows' DMI curve has a greater slope than heifers (Kertz et al., 1991). Roseler et al. (1997) also report a much flatter intake curve for primiparous animals. In our study, however, the DIM $\times$ parity interaction in the DMI model was not significant and the effect of the interaction on water intake was opposite that observed for DMI by previous researchers. One explanation for the greater rate of increase in water intake in primiparous cows is the challenge they face at the onset of lactation when learning to drink from water cups. Before calving, primiparous cows in this study were housed in a free-stall facility equipped with water troughs and were not exposed to individual water cups. During this study multiple observations were made when fresh primiparous cows had trouble operating the water cup in the initial days after calving, possibly resulting in very low water intake. Once the animals learned to use the drinking cups, their intakes increased dramatically, most likely contributing to the greater rate of increase in water intake observed for primiparous cows in this study. This observation underlines the importance of adapting primiparous cows to water cups prepartum to avoid the additional unnecessary stress arising from insufficient water supply postpartum.

Associated Effect of Ambient Temperature and Humidity on Intake

Beatty et al. (2006) report an increase in water intake and decrease in feed intake during periods of increased humidity and ambient temperature in cattle. In our study, however, as RH increased, a decrease in both water intake and DMI was observed. Although significant, the effect of RH was numerically small: a 10% increase in RH would decrease water intake and DMI by 0.839 L and 0.125 kg, respectively. Ambient temperature during the course of our study did not exceed 28.4°C ($\mu = 6.0$, $SD = 11.08$); RH exceeded 80% on 6 d only ($\mu = 50.1\%$, $SD = 16.11$) keeping the temperature-humidity index below 76.6 throughout the study. West et al. (2003) reported no or marginal effects of RH when the temperature-humidity index remained below 77. In ambient temperatures not exceeding 24°C, Meyer et al. (2004) observed a negative correlation between water intake and RH ($r = -0.361$), which is in agreement with the results of this study.

The fact that ambient temperature was not a significant factor in the DMI or water intake models stands

in contrast to previous research (Stockdale and King, 1983; West et al., 2003; Meyer et al., 2004). Meyer et al. (2004) report that for every 1°C increase in ambient temperature, water intake increases by 1.52 kg/d even when ambient temperatures do not exceed 24°C. West et al. (2003) reported a decrease of 0.8-kg of DMI for every 1°C increase. A possible explanation for the lack of observed effect of ambient temperature and the apparent decrease in the measured water intake with increase in RH is change in animal behavior. Because of the exceptionally good ventilation in the St. Paul dairy barn the cows may have only experienced the effect of increased RH and ambient temperature when outside or in the holding pen before milking. Water intake during these periods was not monitored. If cows proportionately increased their intake of water while on pasture or in the holding pen, their measured water intake (from the water cup at stall) may have underestimated actual intake, leading to the observed results.

Relationship Between Water Intake and DMI

The relationship between water intake and DMI was analyzed using 2 models. In model 1, the objective was to investigate whether in a cow pair, DMI change could be approximated by water intake when other covariates (ambient temperature, RH, parity, DIM) were accounted for. Model 2 tested the same hypothesis for a group of 70 animals rather than a cow pair. When investigating the relationship between water intake and DMI, polynomial models including both DIM and DIM² performed best (Table 2). A polynomial model of DMI with terms DIM² and DIM³ has been previously suggested (Kertz et al., 1991). Because of a lack of significant impact on model fit statistics, no interactions were included in either of the final models.

In our attempt to approximate DMI using measured water intake, DMI was more accurately estimated by model 2. Model 2 related average water intakes of a group of 70 animals to their average DMI, as opposed to a pair of cows in model 1 ($R^2 = 0.82$ and $R^2 = 0.50$, respectively). Performance of model 2 suggests the possibility of using water intakes recorded on a larger group of animals as an indirect measure of DMI change for groups of cows. This might prove beneficial for dairy farms with facilities where automation of water intake recording might be a fairly simple and inexpensive investment, which will save time and prevent errors of manual feed intake data collection.

Results of previous research on the relationship between individual DMI and water intake are contradictory. In field trials, Beede (2005) observed that individual cow water intakes deviated by 15 to 20%

Table 2. Structure of the final models of the relationship between DMI and water intake of 35 pairs of cows (model 1, $R^2 = 0.495$) or a group of 70 cows (model 2, $R^2 = 0.817$)

Variable	Model 1			Model 2		
	Estimate	SE	P-value	Estimate	SE	P-value
Intercept	12.900	0.146	<0.001	12.206	0.494	<0.001
Water intake	0.036	0.001	<0.001	0.071	0.008	<0.001
Temperature	-0.072	0.005	<0.001	-0.073	0.012	<0.001
DIM ¹	0.116	0.004	<0.001	0.066	0.011	<0.001
DIM $\times$ DIM	-0.001	0.22×10^{-4}	<0.001	-0.3×10^{-3}	0.75×10^{-4}	<0.001
Parity (>1) ²	1.815	0.068	<0.001	—	—	—

¹DIM represent the average DIM of 2 cows drinking from the same water cup in model 1 and average DIM for the 70 cows in the study in model 2.

²Class-variable parity with 2 levels (1 and >1), representing the average parity of the 2 cows drinking from the same water cup, was included only in model 1.

from the predictions made using those equations cited by the NRC (2001) that include DMI as one of the predicting variables. Meyer et al. (2004) report a correlation coefficient between DMI and water intake of 0.107. Holter and Urban (1992), however, achieved a coefficient of determination of 0.69 (corresponding to $r = 0.83$), whereas Dado and Allen (1994) identified an even stronger relationship between DMI and water intake of individual cows with a correlation coefficient of 0.96. Although total individual DMI were collected during our study, because of the limitations of the water cup installation, we were only able to collect partial water intakes on pairs of cows rather than individual animals. In our study values measured by the water meters accounted for an average of 117% of expected water intake by the model of Holter and Urban (1992) with a range of 52.5 to 184.0% (SD 25.8%). This large variability most likely contributed to the observed small coefficient of determination of the DMI model for pairs of cows. Obtaining total individual water and DM intakes for the whole lactation would give a better view of the true relationship between the 2 variables. It seems, however, that the demonstrated response in water intake to changes in cow status (Table 1) and changes in DMI (Table 2) might make water intake a good potential candidate for monitoring health and

feeding management on the dairy farm, even though further investigation is still needed.

Using Control Charts to Determine Changes in DMI Attributable to Disease or Estrus

The 4 models developed to obtain residuals for the CUSUM charts are presented in Table 3. Coefficients for DMI_{t-1} indicate that autocorrelation of DMI is slightly weaker during the first 3 wk of lactation and among primiparous animals. These findings were also reflected in the difference in the Pearson correlation coefficients between parities (0.85 and 0.87 for primiparous and multiparous cows, respectively) and stages of lactation (0.83 and 0.84 for first 21 DIM and the remaining 129 DIM, respectively). The effect of DIM is more pronounced at the onset of lactation as opposed to mid lactation (Figure 1). This is reflected in the coefficient estimates for DIM >21 being closer to zero (Table 3).

The R^2 values indicate that the models were successful at explaining from 61 to 71% of the variation, leaving room for future improvement by including other variables that influence DMI. Adding factors such as ambient temperature, humidity, or milk yield when data for a full lactation are available should improve

Table 3. Models used to obtain residuals for the cumulative sum (CUSUM) charts¹

Model	Intercept	DMI _(t-1)	DIM	R ²
Heifers				
DIM ≤ 21	4.69 (0.380)***	0.673 (0.030)***	0.081 (0.019)***	0.649
DIM >21	4.69 (0.222)***	0.774 (0.010)***	0.003 (0.002)**	0.614
Cows				
DIM ≤ 21	3.90 (0.307)***	0.783 (0.020)***	0.034 (0.016)*	0.713
DIM >21	4.02 (0.176)***	0.831 (0.007)***	NS	0.698

¹Standard error of estimates indicated in parentheses.

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Figure 1. Average DMI by DIM for primiparous (solid line) and multiparous (dotted line) cows.

model accuracy and further enhance performance of CUSUM charts. Also, to ensure that the models are not herd specific, chart performance testing should be performed on separate data by using either a holdout sample or different herds.

Examples of the proposed charting scheme are presented in Figures 2 and 3. In both figures, panel A represents the actual DMI of the animal. Panel B in both figures represents plotted CUSUM values calculated based on the DMI data presented in panel A. Panel C in Figure 3 shows a Shewhart chart. Any point outside the control limit on any of the panels is considered a sign of a significant shift in DMI. As observed in panel A of Figure 2, calculating CUSUM of the residuals from the DMI model rather than the raw DMI data eliminated the drift and prevented positive CUSUM from rising above the upper control limit as lactation progressed and DMI naturally increased. Panel B in Figure 2 is a CUSUM of location chart that monitors small, sustained changes in mean. A decrease in DMI is observed at 2 DIM and corresponds to the lower CUSUM crossing the lower limit. Mastitis treatment is administered to the cow 2 d later. Although the shift was not sustained, the FIR approach forced the CUSUM to signal a shift. This demonstrates how moving the initial CUSUM from zero to halfway between zero and the lower limit helped detect change in DMI associated with mastitis. Neither the scale CUSUM nor the Shewhart chart signaled any changes (data not presented).

Panels B and C in Figure 3 represent both a scale CUSUM (B) and a Shewhart chart (C). Points outside limits first appear at 55 and 56 DIM on the Shewhart and scale CUSUM chart, respectively. Mastitis treatment is first administered at 58 DIM. The corresponding CUSUM for location did not signal any change. The scale CUSUM chart further signals an increase in variation at 62 DIM, 1 d before the second mastitis

Figure 2. Panels A and B represent cows' observed DMI and cumulative sum (CUSUM) location chart of DMI model residuals, respectively. A) Line marked with triangles represents observed DMI; points marked with solid triangles represent days when mastitis treatment was administered, and points marked with open triangles represent days with no treatment administration. B) Solid lines represent the positive and negative CUSUM, where S is the location CUSUM of DMI model residuals; dashed lines represent the upper and lower limits. The solid circle represents the days when the CUSUM chart signaled a significant drop in mean DMI.

treatment is administered. No signal is observed on the Shewhart chart (panel C) because the shift was too gradual to initiate a signal on a chart that is designed to detect large shifts. The examples presented in Figures 2 and 3 demonstrate the complementary nature of the CUSUM location, CUSUM scale, and Shewhart charts. Each is designed to detect different changes in performance, and using them in combination will improve detection sensitivity.

To further examine the validity of applying CUSUM charts to monitor changes, a statistical evaluation of the sensitivity and specificity of this detection method should be performed. Madsen and Kristensen (2005) present a similar approach to monitoring the health of young pigs through their drinking behavior. Although no statistical evaluation is performed, a series of examples demonstrating the effectiveness of the CUSUM chart in detecting observed or induced changes in animal health is presented. Quimby et al. (2001) were able

Figure 3. Panels A through C represent cows' observed DMI, cumulative sum (CUSUM) for scale, and Shewhart chart, respectively. A) Line marked with triangles represents observed DMI; points marked with solid triangles represent days when mastitis treatment was administered, and points marked with open triangles represent days with no treatment administration. B) Solid line represents the positive scale CUSUM, where V is the scale CUSUM of DMI model residuals; the dashed line represents the upper limit for the scale CUSUM and points marked with solid circles represent days when the CUSUM chart signaled a significant increase in DMI variation. C) Dotted lines represent upper and lower limits for the Shewhart chart, the solid line represents the center line, and U_n is the inverse normal of the Student's T distribution of standardized DMI model residuals. The line marked with squares represents values plotted on the Shewhart chart and the filled square represents the days when the Shewhart chart signaled a significant change in mean DMI.

to determine the sensitivity (91%) of using CUSUM charts to identify morbid steers by monitoring their feeding behavior. De Vries and Conlin (2003) were able to evaluate the performance of a CUSUM chart to detect changes in estrus detection efficiency using a simulation model. Monitoring DMI using combined CUSUM-Shewhart charting scheme has the potential to improve disease and estrus detection. When individual cow water intake data are available, a similar scheme can be developed for detecting disease or estrus by monitoring water intake. Statistical analysis to determine the sensitivity and specificity of CUSUM monitoring to detect changes in cow status can be performed when a sufficient amount of observed individual DMI and water intake data or an appropriate simulation model is available. However, in the current study, the relatively small number of recorded health events limits the possibility of performing a valid statistical evaluation of the method.

CONCLUSIONS

The DMI of individual cows is significantly affected by disease or estrus and can be used for early detection of change in cow health or reproductive status. Although presently cost prohibitive for most commercial dairies, the technology does exist (i.e., Growsafe) to make monitoring of individual cow water and DMI possible, thus facilitating automated daily individual cow intake monitoring. Water intake is strongly correlated with DMI and can serve as an effective indirect measure of DMI change in groups of cows. The relative affordability of automating routine monitoring of water intake makes it an interesting option for monitoring changes in cow feeding behavior on dairy farms. For a group of cows, the suggested application of Shewhart and CUSUM control charts to monitor intake provides a potential scheme to determine with statistical certainty when there has been a change in DM or water intake. On an individual cow basis, identifying significant changes in intake can help detect animals with disease or estrus.

ACKNOWLEDGMENTS

The authors would like to acknowledge the University of Minnesota St. Paul dairy barn staff, Bradley Heins, and Mary Raeth-Knight for their valuable assistance on this project.

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