J. Dairy Sci. 104:5898–5908
https://doi.org/10.3168/jds.2020-19698
© 2021 American Dairy Science Association®. Published by Elsevier Inc. and Fass Inc. All rights reserved.

Association between early postpartum rumination time and peak milk yield in dairy cows

Mateus Peiter, Hannah N. Phillips, and Marcia I. Endres*
Department of Animal Science, University of Minnesota, St. Paul 55108

ABSTRACT

Limited information is available on the relationship between rumination time (RT) in the early postpartum period and milk production later in lactation. Therefore, the objectives of this study were to (1) investigate the association of change in RT and average RT during the immediate postpartum period with peak milk yield (PMY) in dairy cows, and (2) determine the best model based on days in milk (DIM) to evaluate this association. Cows from 33 free-flow automatic milking system farms were included in this study, where retrospective milk production and RT data were collected for 12 mo. Cows were categorized by parity number into parity 1 (P1, n = 1,538), parity 2 (P2, n = 1,354), or parity ≥3 (P3+, n = 1,770). For each cow, PMY was identified as the highest daily milk yield up to 180 DIM for P1 and 120 DIM for P2 and P3+ cows. Five change in RT variables and 5 average RT variables were created corresponding to the first 2 to 6 DIM. Change in RT variables were the slope coefficients for change in RT/d related to DIM = 1 extracted from simple linear regressions, and average RT variables were the arithmetic mean RT. Five models analyzing PMY and corresponding variables calculated over the first 2 to 6 DIM had fixed effects of average RT, change in RT, parity, average RT × parity interaction, change in RT × parity interaction, and a random intercept for farm. Peak milk yield occurred at (median) 75, 44, and 46 DIM for P1, P2, and P3+, respectively. Overall PMY was (mean ± standard deviation) 54 ± 11 kg and it increased as parity increased. A positive association was found between change in RT and PMY, and average RT and PMY for P2 and P3+ cows in all 5 models corresponding to the first 2 to 6 DIM, indicating that greater average RT and quicker increase in RT after calving are associated with greater PMY for multiparous cows. Although the model including all 6 DIM had the greatest accuracy, results indicated that rumination data collected over the first 2 DIM may also provide adequate information for the association of average RT and change in RT with PMY in P2 and P3+ cows. For each 100 min/d increase in change in RT over the first 6 DIM, PMY increased by 4.3 (95% confidence interval: 2.2–6.3) and 4.8 (95% confidence interval: 3.2–6.5) kg for P2 and P3+ cows, respectively. Peak milk yield increased by 2.3 (95% CI: 1.7–2.8) and 2.2 (95% confidence interval: 1.7–2.6) kg for each 100 min increase in average RT over the first 6 DIM for P2 and P3+ cows, respectively. No association was observed between rumination behaviors and PMY for P1 cows. Results from this study indicate that the length of time for multiparous cows to achieve a stable RT in the early postpartum period combined with average RT during the same period may be useful in predicting their overall lactation milk production.
Key words: rumination, peak milk yield, automatic milking system, parity

INTRODUCTION

Automated monitoring of cow behavior using noninvasive technologies is a reality on many dairy farms. For instance, rumination can be accurately measured with different devices by analyzing jaw movements (Kononoff et al., 2002; Braun et al., 2015) or sounds of mastication (Soriani et al., 2012; Elischer et al., 2013; Ambriz-Vilchis et al., 2015). These methods are an alternative to the traditional labor-intensive visual live or video observation and eliminate observer bias and the disruption effect that observers may have on animals. Such devices collect continuous data, which can be stored and used by producers, consultants, and researchers. Furthermore, the sensors can be paired with other technologies, such as the automatic milking system (**AMS**), allowing for the integration of behavior and production data for holistic monitoring of the herd.

Rumination is a cyclical process that consists of regurgitation, remastication, and reswallowing of feed boluses, and it is necessary for particle breakdown and rumen pH balance. Dairy cows ruminate on average 7 to 8 h per day (Zebeli et al., 2006; Soriani et al., 2012), which mostly occurs at night when there are fewer dis-

Received September 25, 2020.
Accepted January 11, 2021.
*Corresponding author: miendres@umn.edu

ruptive management tasks being performed (Pahl et al., 2015; Beauchemin, 2018).

Rumination time (**RT**) decreases on average by 70% of the average RT observed during the dry period on the day of calving (Calamari et al., 2014), reaching a minimum daily average of approximately 4 h (Soriani et al., 2012; Kaufman et al., 2016). Rumination time in the prepartum period was shown to be associated with postpartum RT (Soriani et al., 2012; Liboreiro et al., 2015).

The metabolic and health status of the cow during the transition period are associated with deviations in RT. Numerous previous studies reported an association between decreased RT and metabolic or digestive disorders, such as subclinical ketosis, displaced abomasum, indigestion, and ruminal acidosis (DeVries et al., 2009; Kaufman et al., 2016; Stangaferro et al., 2016). Similarly, other studies reported that RT decreased during lameness and pneumonia events (King et al., 2017; King and DeVries, 2018). Furthermore, cows that delivered twins exhibited a decrease in postpartum RT compared with cows that delivered singletons, which was likely explained by uterine and metabolic issues related to the occurrence of twins (Liboreiro et al., 2015). Soriani et al. (2012) found that cows that underwent a severe inflammatory response in the peripartum period had a reduced RT in early lactation. Therefore, the aforementioned studies provide evidence that RT may be used as a proxy for cow health in the postpartum period, where subtle changes in RT may indicate a health disorder in early lactation.

Furthermore, early lactation RT has been shown to be positively associated with short-term milk yield (**MY**; Liboreiro et al., 2015; Stone et al., 2017; Kaufman et al., 2018), which may have been due to healthier animals and rumens, and increased feed intake. Cows with greater RT from 3 to 6 DIM produced up to 8 kg more milk per day during the first 30 DIM (Calamari et al., 2014). Additionally, King et al. (2017) showed that RT and MY followed a similar pattern around the period of disease diagnosis, where both began to decrease a few days before disease detection. Lactation peak milk yield (**PMY**) normally occurs between 45 and 100 DIM, with primiparous cows peaking later than multiparous cows (Siewert et al., 2019). In a simple linear regression model, Mellado et al. (2011) showed that PMY accounted for most the variability in total 305-d MY ($R^2 = 0.69$), where each 1 kg increase in PMY was associated with a 157 kg increase in total 305-d MY on average. However, the association between immediate postpartum RT and PMY has not been documented. Daily values of RT are more commonly used as a predictor of health and production in most studies. Nevertheless, it has been speculated that the change in RT over a certain period may be a preferred predictor as opposed to daily RT values (Liboreiro et al., 2015). Therefore, the objectives of this study were to (1) investigate the association of change in RT and average RT during the immediate postpartum period with PMY in dairy cows, and (2) determine the best statistical model based on number of DIM to evaluate this association. We hypothesized that cows with a greater postpartum change in RT and with a greater average postpartum RT would have greater PMY.

MATERIALS AND METHODS

Data were collected from 33 AMS farms in the United States (located in Minnesota and Wisconsin). All farms in this study used a free-flow cow traffic system, such that cows had unrestricted access to all areas of the pen, including the AMS. Retrospective data recorded daily on cow production and RT were collected from the AMS software (T4C, Lely Industries) for a period of 12 mo during the years of 2017 and 2018. The data included cow identification and respective parity, total daily MY (kg), and total daily RT (min). Herds enrolled in this study consisted of Holsteins and all the cows were housed in freestall barns with no access to pasture.

Rumination time was measured using Hi-Tag rumination sensors (SCR Engineers), in which the logger was positioned on the left side of the neck and held in place by a collar. A built-in microphone recorded sounds of regurgitation and rumination, which were aggregated by the software and displayed as 24-h daily RT in minutes. The Hi-Tag rumination monitoring system was validated as a tool to accurately measure RT when compared with direct human observation, Pearson's r = 0.93, $P < 0.001$ (Schirmann et al., 2009).

Data Processing and Statistical Analysis

All postcollection data management procedures and statistical analyses were performed in RStudio (R Core Team, 2020). The variable DIM represented the day of the lactation period, which began with 1 following the day of calving. Day of calving (i.e., DIM = 0) was removed from the data set, as cows calved at different times of day resulting in less than 24 h of data. Cows were categorized according to parity: parity 1 (**P1**), parity 2 (**P2**), or parity ≥3 (**P3+**). New variables for PMY (kg) and DIM at peak (d) were created, which described the highest daily MY for each cow. A data-driven threshold of 180 DIM for P1 cows and 120 DIM for P2 and P3+ cows was established for the identification of PMY, which represented the range of DIM where the vast majority of cows in this study reached the highest daily MY. Daily RT continued to increase from DIM 1 until DIM 6 when it reached stable levels; therefore, only the first 6 DIM were considered for calculating early-lactation rumination predictor variables, as the change in RT was of interest to build the statistical model. Daily MY for the first 150 DIM and daily rumination for the first 14 DIM were visually assessed before analyses by plotting the estimated local averages and standard errors from generalized additive models fit with a cubic spline by parity group.

Data cleansing was performed before analyses to improve the quality of the data by diagnosing and removing faulty data (Van Den Broeck et al., 2005). Lactation periods had to meet the following criteria or else they were removed: (1) complete daily RT observations for the first 6 DIM that had values ≥30 min; (2) a length of ≥120 d for P1 or ≥90 d for P2 and P3+; (3) no missing MY observations before identified PMY; (4) DIM at peak ≥7 d. Last, repeated lactations within cow were removed, and the longest lactation meeting the selection criteria remained in the data set. Daily MY observations were considered outliers and not used when MY had a z-score ≥1.96, which was calculated based on 7-d MY averages for each cow [z = (MY − 7-d MY average)/7-d SD for MY]. Furthermore, a sample of random lactations with a wide range of DIM at peak was plotted for visual inspection of potential influential MY observations, to ensure that the identified PMY was not driven by outlier observations. The final data set included 4,662 cows with one lactation each. The number of cows from each farm ranged from 34 to 416.

To demonstrate the differences in average RT and change in RT between different levels of PMY, we assigned cows to a production category within each farm and parity corresponding to percentiles for PMY values: ≥0.75 (top; **T25**) and ≤0.25 (low; **L25**). For these analyses, each model had either change in RT or average RT as the outcome variable, and fixed effects of PMY percentile category, parity, PMY percentile category × parity interaction, and a random intercept for farm.

Association of Change in RT and Average RT with PMY. Peak milk yield was used as the outcome variable in 6 mixed linear regression models using the lmer function of the lme4 package (Bates et al., 2015), which corresponded to the number of DIM, ranging from 1 to 6, used to calculate the predictor variables based on RT. Five changes in RT variables were created, which corresponded to the slope coefficients for change in RT/d related to DIM = 1 extracted from simple linear regressions performed for each cow and for each of the first 2 to 6 DIM as continuous predictors with RT as the outcome variable. For instance, the change in RT over the first 6 DIM was the linear regression slope representing the change in RT from 1 to 6 DIM. The same procedure was done for the first 2, 3, 4, and 5 DIM for each cow. Similarly, 5 average RT variables were created, which corresponded to the arithmetic mean RT for each cow over the first 2 to 6 DIM. Last, a variable was created for the RT on DIM = 1. Therefore, 11 rumination variables were calculated for each cow. The Pearson's correlation coefficients between average RT and change in RT were r = −0.04 for the model containing the first 2 DIM, r = 0.02 over the first 3 DIM, r = 0.05 over the first 4 DIM, r = 0.05 over the first 5 DIM, and r = 0.06 for the model with 6 DIM. It is suggested that a collinearity problem exists when factors with a Pearson's r > 0.7 are included in the same statistical model (Dormann et al., 2013; Tremblay et al., 2016). Therefore, we included both average RT and change in RT in the final model.

For the statistical analyses of PMY, the 5 models corresponding to rumination predictor variables calculated over the first 2 to 6 DIM had PMY as outcome variable, with fixed effects of average RT (continuous), change in RT (continuous), parity (3 levels), the average RT × parity interaction, the change in RT × parity interaction, and a random intercept for farm (33 levels). In other words, each of the 5 models included 2 variables for rumination: the change in RT and the average RT over a specific period. For example, the model for 2 DIM had change in RT over the first 2 DIM (with respect to DIM 1) and the average RT for the first 2 DIM included as predictor variables. The model corresponding to RT on DIM = 1 as a predictor variable had fixed effects of RT (continuous), parity, RT × parity interaction, and a random intercept for farm.

Model Fit and Significance. For each model, the root mean square error, marginal R^2 coefficient ($\mathbf{R^2_{(m)}}$), and conditional R^2 coefficient ($\mathbf{R^2_{(c)}}$) were calculated using tools in the merTools and MuMIn packages (Barton, 2019; Knowles and Frederick, 2020). Model fit was assessed by visual observation of residual plots. The denominator degrees of freedom were estimated using Satterthwaite's method. Restricted maximum likelihood estimates were obtained, and means are reported as least squares means. Graphical visualizations of data were created using tools of the ggplot2 package (Wickham, 2016). Significance was declared at $P \leq 0.05$. The Tukey P-value adjustment was used for pairwise comparisons.

RESULTS AND DISCUSSION

The population of cows (n = 4,662) in this observational study was composed of 33% P1 (n = 1,538), 29%

P2 (n = 1,354), and 38% P3+ (n = 1,770) cows. The DIM at peak variable had a right-skewed distribution; therefore, the median is reported. The median DIM at peak was 52 (range: 7 to 180) across all parity groups. A recent study using 2013–2014 data from cows milked in AMS found that P1 cows reached PMY between 89 and 148 DIM, on average (Siewert et al., 2019). Likewise, Mellado et al. (2011) reported mean PMY at 123 DIM for P1 cows milked 3 times daily in a conventional parlor and injected with recombinant bST. Primiparous cows in the current study reached lactation peak considerably sooner, at a median of 75 DIM, ranging from 11 to 180 DIM. This may indicate that AMS farmers are adopting management strategies that allow P1 cows to adapt to the AMS more easily and consequently reach peak earlier in their lactation. Second- and third-parity cows in the current study peaked at a median of 44 (range: 8–120) and 46 (range: 7–120) DIM, respectively, in agreement with Siewert et al. (2019), who reported the peak for multiparous cows (P2 and P3+ combined) between 29 and 58 DIM, on average. However, multiparous cows housed in open lots peaked at a mean of 106 DIM according to a previous study (Mellado et al., 2011), which is considerably later than cows in our study. Differences in genetics, nutrition, housing, management, and weather conditions may explain the discrepancy in days to reach peak, as the latter study was conducted on a dairy farm in Mexico (Mellado et al., 2011).

Peak milk yield for cows in this study had an overall arithmetic mean of 53.6 ± 11.4 kg. The mean ± SD PMY was 43.1 ± 6.7 kg (range: 18.8–66.6 kg), 56.2 ± 8.8 (range: 21.1–84.9 kg), and 60.7 ± 9.7 (range: 20.6–89.1 kg) for cows in P1, P2, and P3+, respectively. Cows in P2 and P3+ had greater PMY than P1 cows, which was expected considering that primiparous cows have a biologically normal lower PMY compared with P2 and P3+ cows (Figure 1). Peak milk ratio was 0.77 and 0.71 between P1 and P2, and P1 and P3+ cows, respectively. Similarly, Siewert et al. (2019) reported a peak milk ratio between primiparous and multiparous cows (P2 and P3+ combined) of 0.71 to 0.74, depending on cow traffic flow. The industry recommended PMY for P1 cows has been 80% of the PMY of P2 cows and 75% of PMY of P3+ cows (Bailey and Currin, 2009). However, the latter authors considered lactation peak for P1 cows to be between 41 and 100 DIM based on DHIA records, which are generally based on a once monthly sample collection per cow. Therefore, we suggest that the PMY reported herein and found by Siewert et al. (2019) might be a more accurate representation of the actual lactation peak of cows on AMS dairy farms, as both studies used complete daily MY observations.

The average PMY was (mean ± SD) 44.3 ± 8.8 kg and 62.7 ± 10.0 kg for cows in the L25 (n = 1,215; P1 = 399, P2 = 357, P3+ = 459) and T25 (n = 1,211; P1 = 398, P2 = 355, P3+ = 458) categories for PMY, respectively, where cows in the T25 category had a 42% greater PMY compared with L25. The median DIM at peak was 52 (range: 7–180 DIM) for L25, and 54 (range: 9–178 DIM) for T25. Least squares means for change in RT and average RT by parity and PMY percentile category are shown in Table 1. These results are provided to demonstrate the difference in RT parameters among parities. For P1 cows, there was no difference in change in RT and average RT between PMY percentile categories, whereas P2 and P3+ cows categorized as T25 for PMY had a greater change in RT and average RT compared with the L25 category in all statistical models. The differences in RT are clear in Figure 2, where daily RT over the first 14 DIM is shown for the interaction between PMY percentile category and parity.

In recent years, information derived from rumination behaviors automatically monitored with sensors has been largely used for predicting a variety of outcomes, which has potential benefits of reduced human labor and minimal disruption of the animals. Important events in the life of a dairy cow, such as estrus and calving, can be predicted using RT (Reith and Hoy, 2012; Pahl et al., 2015; Schirmann et al., 2016). Furthermore,

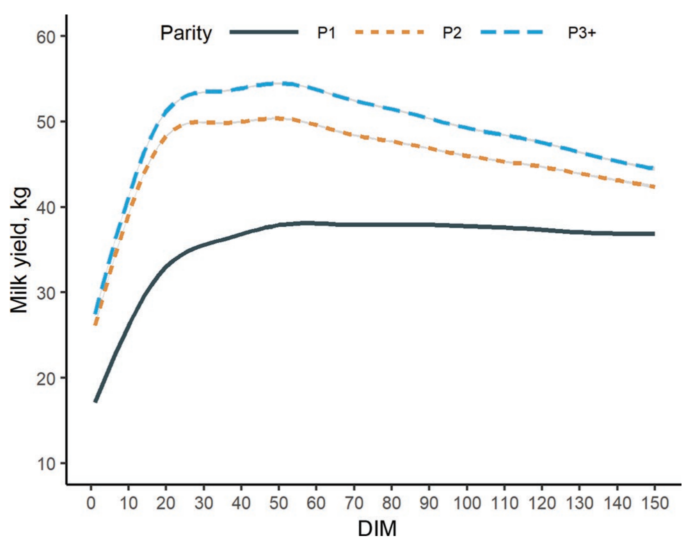

Figure 1. Estimated local averages and SE (gray bands) for daily milk yield (kg) during the first 150 DIM calculated from a generalized additive model fit with a cubic spline for parity 1 (P1; solid black line), parity 2 (P2; short-dashed orange line), and parity ≥3 (P3+; long-dashed blue line). n = 4,662 cows from 33 automatic milking system dairy farms in the United States.

Table 1. Least squares means ± SE[1] of average rumination time (RT; min) and change in RT (min/d) for the interaction between peak milk yield (PMY) percentile[2] and parity[3] for 4,662 cows from 33 automatic milking system dairy farms in the United States

	P1		P2		P3+	
Item	L25 (n = 402)	T25 (n = 399)	L25 (n = 358)	T25 (n = 354)	L25 (n = 457)	T25 (n = 458)
Average RT, min						
1 DIM	299 ± 7	306 ± 7	306 ± 7[b]	330 ± 7[a]	272 ± 7[b]	287 ± 7[a]
2 DIM	317 ± 7	319 ± 7	326 ± 7[b]	358 ± 7[a]	296 ± 7[b]	322 ± 7[a]
3 DIM	333 ± 7	335 ± 7	345 ± 7[b]	381 ± 7[a]	315 ± 7[b]	346 ± 7[a]
4 DIM	344 ± 7	350 ± 7	360 ± 7[b]	397 ± 7[a]	332 ± 7[b]	367 ± 7[a]
5 DIM	353 ± 7	360 ± 7	371 ± 7[b]	411 ± 7[a]	347 ± 6[b]	383 ± 6[a]
6 DIM	360 ± 6	368 ± 6	381 ± 7[b]	423 ± 7[a]	359 ± 6[b]	396 ± 6[a]
Change RT,[4] min/d						
2 DIM	34.7 ± 5.3	26.2 ± 5.3	39.1 ± 5.5[b]	57.3 ± 5.5[a]	48.1 ± 5.0[b]	68.4 ± 5.0[a]
3 DIM	32.1 ± 3.2	30.6 ± 3.2	38.6 ± 3.3[b]	47.7 ± 3.3[a]	40.2 ± 3.0[b]	54.2 ± 3.0[a]
4 DIM	26.4 ± 2.2	29.5 ± 2.2	33.1 ± 2.3[b]	39.3 ± 2.3[a]	37.2 ± 2.1[b]	46.0 ± 2.1[a]
5 DIM	22.5 ± 1.6	24.8 ± 1.6	27.8 ± 1.7[b]	33.7 ± 1.7[a]	33.0 ± 1.6[b]	39.9 ± 1.6[a]
6 DIM	18.5 ± 1.3	20.8 ± 1.3	24.4 ± 1.4[b]	29.4 ± 1.4[a]	29.2 ± 1.3[b]	33.8 ± 1.3[a]

[a,b]Means without a common letter within row and parity are different at $P < 0.05$.

[1]Statistical models corresponding to the number of DIM included in the calculation of rumination parameters with average RT [6 models (1–6 DIM)] and change in RT [5 models (2–6 DIM)] as outcome variables, and PMY percentile category, parity, and their interaction as predictor variables, considering farm as the random intercept.

[2]PMY percentile within farm and parity: L25 = ≤0.25 quantile; T25 = ≥0.75 quantile.

[3]Parity: P1 = parity 1; P2 = parity 2; P3+ = parity ≥3.

[4]Simple linear regression slope coefficient for daily RT.

King et al. (2017) suggested that RT starts to decrease as early as 14 d before the diagnosis of health disorders, such as pneumonia and lameness. Rumination time has been shown to be associated with various health and metabolic disorders during the early postpartum period. Soriani et al. (2012) reported a negative correlation of prepartum and early postpartum average RT with nonesterified fatty acids and BHB values during the postpartum period (Pearson's r = −0.35, $P < 0.001$). A recent study reported that cows with subclinical ketosis had a reduced RT compared with healthy cows from 0 to 8 DIM (Liboreiro et al., 2015). The latter authors also showed that cows with retained placenta had a decreased RT from 2 to 7 DIM, and cows diagnosed with metritis exhibited a reduced RT from 2 to 9 DIM, when compared with healthy cows (Liboreiro et al., 2015). Furthermore, hypocalcemic cows at calving had a lower RT at 1 DIM compared with healthy cows (Liboreiro et al., 2015). Calamari et al. (2014) showed that 91% of cows in the <0.50 quantile for RT from 3 to 6 DIM were diagnosed with at least one clinical disease in the early postpartum period, whereas only 42% of cows in the ≥0.50 quantile for RT from 3 to 6 DIM had been diagnosed with a clinical disease. Therefore, we suggest that RT may be used as a proxy for dairy cow health, especially during the early lactation period when cows are more susceptible to health disorders, which can then affect their overall milk production, including lactation PMY.

Association Between Change in RT and PMY

To our knowledge, the association between change in RT in the immediate postpartum period and PMY has not been investigated. Our results (Table 2) show a positive association between the change in RT in the early postpartum and the outcome of PMY (model 2 DIM: $F_{1,4632} = 18.6$, $P < 0.0001$; model 3 DIM: $F_{1,4635} = 23.2$, $P < 0.0001$; model 4 DIM: $F_{1,4635} = 29.9$, $P < 0.0001$; model 5 DIM: $F_{1,4633} = 34.5$, $P < 0.0001$; model 6 DIM: $F_{1,4634} = 34.5$, $P < 0.0001$); however, the association differs by parity, as indicated by an interaction between change in RT and parity for the models from 2 to 6 DIM (model 2 DIM: $F_{2,4624} = 14.9$, $P < 0.0001$; model 3 DIM: $F_{2,4624} = 17.3$, $P < 0.0001$; model 4 DIM: $F_{2,4624} = 9.0$, $P = 0.0001$; model 5 DIM: $F_{2,4624} = 7.8$, $P = 0.0004$; model 6 DIM: $F_{2,4624} = 5.3$, $P = 0.005$). Change in RT was not associated with PMY for P1 cows in any of the models. For cows in P2 and P3+, change in RT was associated with PMY in all models from 2 to 6 DIM. For each 100 min/d increase in change in RT across models, the coefficients for the increase in PMY (model 2 DIM–model 6 DIM) ranged between 1.04 and 4.26 kg and 1.15 and 4.84 kg for cows in P2 and P3+, respectively (Table 2). The association between change in RT and PMY was not different between cows in P2 and P3+. Figure 4 shows these associations by reporting the least squares means of PMY for the interaction between parity and change in

RT for the model 6 DIM. A similar pattern was found for models 2 to 5 DIM (graphs not shown). A greater positive change in RT indicates that cows increased their daily RT more rapidly after calving, and these are most likely healthier cows during the early postpartum period. Calamari et al. (2014) showed that cows take between 3 and 15 d to restore a stable level of daily RT after calving. In the current study, individual cows reached a stable daily RT at 6.2 ± 1.2 DIM, ranging from 5 to 12 DIM (Figure 3). A future algorithm for the prediction of PMY should consider including different variables for primiparous and multiparous cows, as based on the findings of the current study change in RT was associated with PMY for cows in P2 and P3+, but not for P1 cows. The possible reasons for this difference between P1 and multiparous cows were not investigated in the current study. The fact P1 cows generally have a considerably lower PMY along with a less steep increase in daily RT in the early postpartum in comparison with multiparous cows could partially explain such findings. However, further research is warranted to better understand the lack of association between early postpartum change in RT and PMY in P1 cows.

The individual cow change in RT related to RT at DIM = 1 ranged from −353 to +431 min/d over the first 2 DIM, −195 to +322 min/d over the first 3 DIM, −131 to +207 min/d over the first 4 DIM, −103 to +164 over the first 5 DIM, and −80 to +136 min/d over the first 6 DIM. The range for change in RT decreased as the number of days included in the calculations increased. A significant number of cows were identified with a negative change in RT in early postpartum, such that their RT decreased relative to RT on DIM = 1. Negative values for change in RT were identified in 28, 19, 13, 11, and 9% of the cows in this study when calculated over the first 2, 3, 4, 5, and 6 DIM, respectively. This phenomenon was unexpected since the day of calving typically represents the time point when the lowest daily RT of approximately 4 h is observed (Soriani et al., 2012; Kaufman et al., 2016; Figure 3). Although health events were not collected for this study, it is reasonable to suggest that cows with a negative change in RT may have been experiencing serious issues related to transitioning. A greater change in RT was associated with greater PMY in the current study for multiparous cows, where each 100 min/d increase in RT resulted in up to 4.84 kg greater PMY. Ensuring that transition cows are healthy and have quality feed available at all times may increase RT in the early postpartum period and improve productivity and profitability on dairy farms. Our research suggests that the change in RT in early lactation may be used for future predictions of PMY, where data from the first 2 to 6 DIM resulted in useful associations for predictions. However, further research investigating other cow- and herd-level factors is encouraged.

Association Between Average RT and PMY

Although the association between change in RT in early postpartum and PMY has not yet been investi-

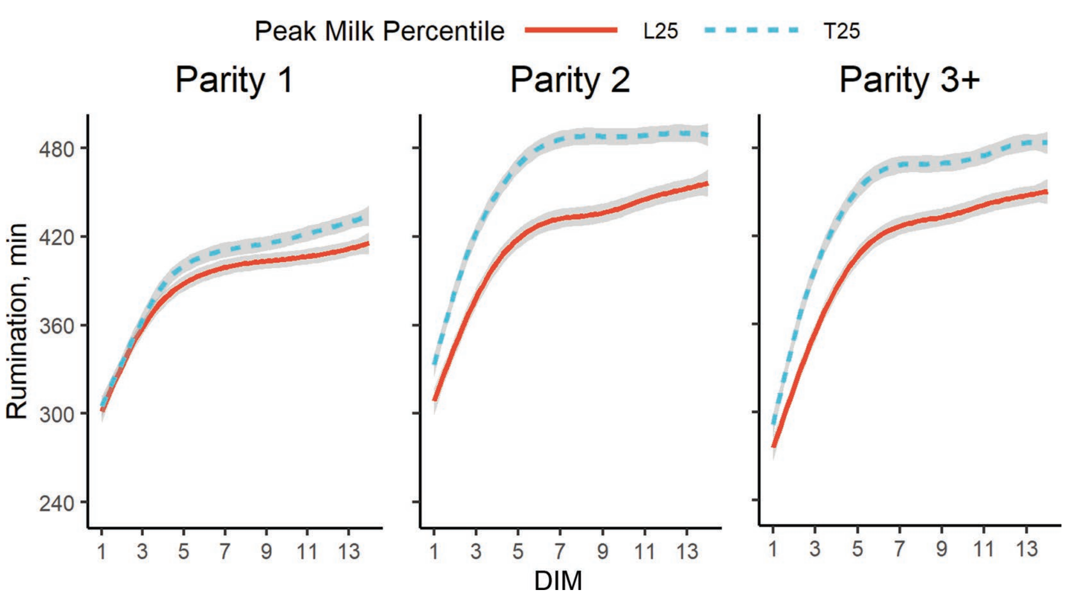

Figure 2. Estimated local averages and SE (gray bands) for daily rumination time (min) during the first 14 DIM calculated from a generalized additive model fit with a cubic spline for each parity for the ≤0.25 quantile (L25; solid red line) and ≥0.75 quantile (T25; long-dashed blue line). n = 4,662 cows from 33 automatic milking system dairy farms in the United States.

Table 2. Fixed effect regression coefficients and 95% CI[1] for the mixed linear regression model with peak milk yield (PMY; kg) as outcome variable and farm as random effect by parity[2] for 4,662 cows from 33 automatic milking system dairy farms in the United States

	Parity			*P*-value[3]				
Coefficient, kg	P1 (n = 1,538)	P2 (n = 1,354)	P3+ (n = 1,770)	P	Ch RT	AvgRT	P × Ch RT	P × Avg RT
Model 1 DIM				***		**		NS
Intercept	42.0 [40.1, 43.9][c]	53.4 [51.4, 55.4][b]	59.3 [57.7, 61.0][a]					
RT	0.18 [−0.24, 0.61]	0.68 [0.23, 1.13]	0.29 [−0.05, 0.63]					
Model 2 DIM[4]				***	***	***	***	**
Intercept	42.6 [40.5, 44.7][c]	50.5 [48.3, 52.7][b]	56.3 [54.5, 58.2][a]					
Change RT[5]	−0.44 [−0.90, 0.03][b]	1.04 [0.54, 1.55][a]	1.15 [0.76, 1.54][a]					
Average RT	0.03 [−0.45, 0.53][b]	1.34 [0.84, 1.83][a]	1.02 [0.63, 1.41][a]					
Model 3 DIM				***	***	***	***	***
Intercept	42.6 [40.4, 44.9][c]	49.1 [46.8, 51.4][b]	54.1 [52.2, 56.1][a]					
Change RT	−0.67 [−1.50, 0.16][b]	1.60 [0.73, 2.47][a]	2.52 [1.84, 3.21][a]					
Average RT	0.04 [−0.49, 0.57][b]	1.60 [1.10, 2.11][a]	1.45 [1.04, 1.85][a]					
Model 4 DIM				***	***	***	**	***
Intercept	42.0 [39.6, 44.3][c]	47.7 [45.4, 50.1][b]	52.9 [50.9, 54.9][a]					
Change RT	−0.04 [−1.21, 1.14][b]	2.45 [1.18, 3.72][a]	3.24 [2.24, 4.24][a]					
Average RT	0.17 [−0.38, 0.73][b]	1.85 [1.33, 2.36][a]	1.68 [1.26, 2.10][a]					
Model 5 DIM				***	***	***	**	***
Intercept	41.6 [39.2, 44.1][c]	46.4 [44.0, 48.9][b]	51.4 [49.2, 53.5][a]					
Change RT	0.29 [−1.26, 1.83][b]	3.34 [1.70, 4.98][a]	4.27 [2.98, 5.57][a]					
Average RT	0.24 [−0.33, 0.81][b]	2.08 [1.56, 2.60][a]	1.98 [1.55, 2.41][a]					
Model 6 DIM				***	***	***	**	***
Intercept	41.3 [38.8, 43.8][c]	45.3 [42.8, 47.8][b]	50.5 [48.3, 52.7][a]					
Change RT	0.80 [−1.14, 2.75][b]	4.26 [2.21, 6.32][a]	4.84 [3.23, 6.45][a]					
Average RT	0.31 [−0.27, 0.89][b]	2.26 [1.74, 2.79][a]	2.15 [1.71, 2.59][a]					

[a–c]Estimates without a common letter within a row are different at $P < 0.05$.

[1]Coefficients and 95% CI for rumination time (RT), change in RT, and average RT are multiplied by 100. Therefore, for each 100 min or min/d increase in a certain fixed effect, PMY increases or decreases by [coefficient] kg.

[2]Parity: P1 = parity 1; P2 = parity 2; P3+ = parity ≥3.

[3]*F*-test *P*-values: P = parity; Ch RT = change in RT; Avg RT = average RT; P × Ch RT = parity × change in RT interaction; P × Avg RT = parity × average RT interaction.

[4]Each statistical model corresponds to the number of DIM included in the calculation of rumination parameters. For instance, model 2 DIM includes the average RT for the first 2 DIM and change in RT over the first 2 DIM with respect to DIM = 1.

[5]Simple linear regression slope coefficient for daily RT.

NS ≥0.05; **<0.01 and ≥0.0001; ***<0.0001.

gated, the association between early lactation RT and MY has been previously documented. Average MY in the first 90 DIM has been shown to have a moderate positive association with 21-d average postpartum RT (Pearson's r = 0.42, $P < 0.01$; Liboreiro et al., 2015). Calamari et al. (2014) found that cows with greater RT during 3 to 6 DIM had a greater average MY during the first month of lactation, resulting in almost 8 kg more milk per day. Moreover, a recent study showed that every 30-min increase in daily RT was associated with an increase in MY of approximately 0.2 kg/d for P1 and 0.5 kg/d for P2 cows from 4 to 28 DIM, and every 30-min increase in daily RT was associated with a 1.2 kg/d increase in MY for P3+ cows during the first week of lactation (Kaufman et al., 2018).

In the current study, the average RT across parity groups ranged from 301 min at 1 DIM to 383 min over the first 6 DIM, with individual daily RT ranging from 30 to 664 min. Our findings showed that average RT was associated with PMY in all statistical models (model 1 DIM: $F_{1,4645} = 9.8$, $P = 0.0017$; model 2 DIM: $F_{1,4647} = 32.5$, $P < 0.0001$; model 3 DIM: $F_{1,4649} = 48.5$, $P < 0.0001$; model 4 DIM: $F_{1,4650} = 64.6$, $P < 0.0001$; model 5 DIM: $F_{1,4651} = 82.3$, $P < 0.0001$; model 6 DIM: $F_{1,4651} = 96.1$, $P < 0.0001$), yet there was an interaction between average RT and parity (model 2 DIM: $F_{2,4625} = 7.7$, $P = 0.0004$; model 3 DIM: $F_{2,4625} = 11.6$, $P = 0.0001$; model 4 DIM: $F_{2,4625} = 12.3$, $P < 0.0001$; model 5 DIM: $F_{2,4625} = 14.7$, $P < 0.0001$; model 6 DIM: $F_{2,4625} = 16.1$, $P < 0.0001$). Similar to the change in RT, there was no association between average RT and PMY for P1 cows in any of the models. However, average RT was associated with PMY in all models from 2 to 6 DIM for cows in P2 and P3+. For each 100 min increase in average RT across models, the regression coefficients for the increase in PMY (model 2 DIM–model 6 DIM) ranged between 1.34–2.26 kg, and 1.02–2.15 kg for cows in P2 and P3+, respectively (Table 2). The association of average RT with PMY was not different between cows in P2 and P3+ regardless of the model. Figure 4 shows these associations by reporting the least squares means of PMY for the interaction between parity and average RT for the model 6 DIM. A similar pattern was found for models 2 to 5 DIM.

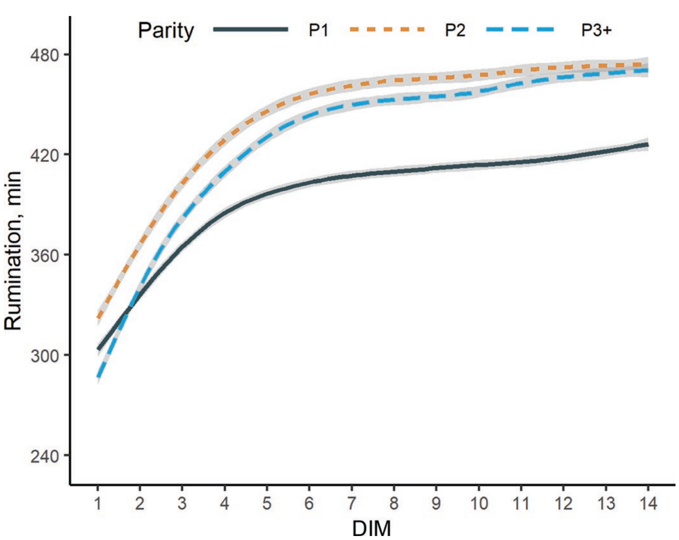

Figure 3. Estimated local averages and SE (gray bands) for daily rumination time (min) during the first 14 DIM calculated from a generalized additive model fit with a cubic spline for parity 1 (P1; solid black line), parity 2 (P2; short-dashed orange line), and parity ≥3 (P3+; long-dashed blue line). n = 4,662 cows from 33 automatic milking system dairy farms in the United States.

Primiparous cows are known for having a lower average RT compared with multiparous cows. Soriani et al. (2012) reported that P1 cows had a consistently lower RT compared with multiparous cows (P2 and P3+) from 10 d prepartum until 40 DIM, and they suggested that P1 cows may display a lower RT due to the greater stress of environmental changes in early lactation compared with multiparous cows. Figure 3 shows that P1 cows in the current study indeed had a lower average daily RT compared with cows in P2 and P3+ during the first 14 DIM. Moreover, P1 cows normally have lower DMI in comparison with P2 and P3+ cows (Janovick and Drackley, 2010), which is expected as rumen capacity is positively correlated with body size (De Boever et al., 1990). However, even when adjusted to a percentage of BW, DMI is reduced in P1 cows (Maekawa et al., 2002). The latter authors found that P1 cows had decreased DMI and also decreased RT compared with multiparous cows (Maekawa et al., 2002). Therefore, a lower average RT in early lactation along with a normally lower PMY for P1 cows could partially explain the lack of association between average early postpartum RT and PMY for this parity group.

Model Comparison

Considering the model fit parameters presented in Table 3, the model using data from the first 6 DIM explains the variability of the data the best—with lowest root mean square error, and greatest $R^2_{(m)}$ and $R^2_{(c)}$ coefficients. However, data collected from only 2 to 3 DIM are capable of generating similar model fit for the association of RT variables and PMY. We decided to use only data for the first 6 DIM after a preliminary exploration of the data, which showed the average daily RT leveling off starting at 7 DIM (Figure 3). For the current study, including both change in RT and aver-

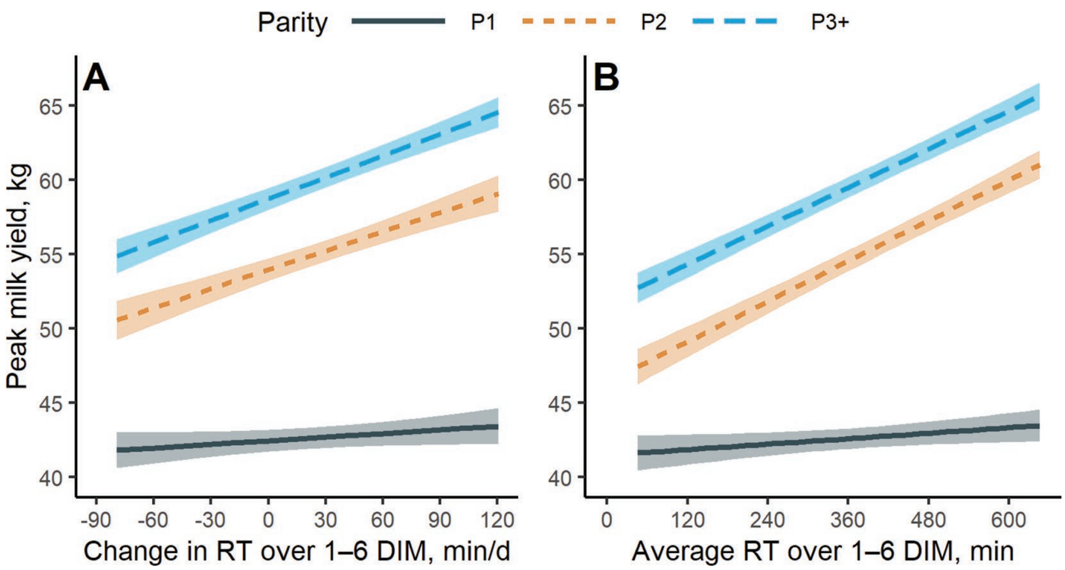

Figure 4. Least squares means and SE (transparent bands) of peak milk yield (PMY; kg) for the interaction between parity and (A) change in rumination time (RT) for the first 6 DIM (min/d), and (B) average RT for the first 6 DIM (min). Parity 1 (P1) = solid black line, parity 2 (P2) = short-dashed orange line, and parity ≥3 (P3+) = long-dashed blue line. Fixed effects model: PMY = parity + change in RT over first 6 DIM + average RT over first 6 DIM + parity × change in RT over first 6 DIM + parity × average RT over first 6 DIM. *P*-values of fixed effects: parity <0.0001; change in RT over first 6 DIM <0.0001; average RT over first 6 DIM <0.0001; parity × change in RT over first 6 DIM = 0.01; parity × average RT over first 6 DIM <0.0001. n = 4,662 cows from 33 automatic milking system dairy farms in the United States.

age RT in the statistical model improved the model fit and should therefore both be considered as predictors of PMY. Ultimately, a prediction algorithm may be created to predict PMY using change in RT and average RT along with other factors to help producers make management decisions. Cows with reduced RT in early lactation may decrease PMY and overall lactation productivity. The prediction of such an outcome early on could help producers decide if, for instance, a special treatment or potential early removal from the herd is an option for those animals. Caution is warranted when generalizing results from the current study, considering that it was performed in a single geographical location, where all farms had the same type of housing and milking system. Furthermore, the analyses and the results of the current study are based on averages for thousands of cows across 33 dairy farms. Therefore, the associations found herein are not predictions and may differ at the cow level.

Table 3. Model fit parameters of the 6 mixed linear regression models predicting peak milk yield, which included predictors of change in rumination time, average rumination time, parity, and a random effect of farm

Model	RMSE[1]	Conditional R^2	Marginal R^2
1 DIM	7.81	0.54	0.43
2 DIM	7.74	0.55	0.44
3 DIM	7.70	0.55	0.45
4 DIM	7.69	0.56	0.45
5 DIM	7.66	0.56	0.45
6 DIM	7.65	0.56	0.45

[1]Root mean square error.

CONCLUSIONS

It was interesting to learn that the time it took to reach a more stable RT in the early postpartum period was not associated with PMY for primiparous cows; however, it appeared to be an important factor associated with PMY for multiparous cows. Results of this study indicate that multiparous cows that increase RT to stable levels more rapidly and with greater average daily RT soon after parturition may produce more milk during their lactation. Therefore, these rumination behavior indicators could help producers make management decisions related to animal health or early removal of cows from the herd. Even though the model with 6 DIM resulted in a better accuracy, the use of data over the first 2 DIM generated similar results. Furthermore, findings of this study warrant for future investigations using data collected via sensors and automatic milking systems.

ACKNOWLEDGMENTS

We thank all the dairy farmers who allowed us to have access to their data. We thank Lely (Lely Industries, Maassluis, the Netherlands) for technical help with data collection from the AMS software. In addition, we thank Form-A-Feed (Brant Groen, Stewart, MN) for partial financial support of on-farm data collection, and Emily Irwin (Form-A-Feed intern) for visiting the farms to collect the data. Mateus Peiter was partially supported by the College of Food, Agricultural and Natural Resource Sciences (University of Minnesota, St. Paul) MnDRIVE Graduate Student Professional Development Award and the Hueg-Harrison Fellowship, and also the John Brandt Memorial Fund Scholarship (Land O'Lakes Foundation, Land O'Lakes Inc., St. Paul, MN). The authors have not stated any conflicts of interest.

REFERENCES

Ambriz-Vilchis, V., N. S. Jessop, R. H. Fawcett, D. J. Shaw, and A. I. Macrae. 2015. Comparison of rumination activity measured using rumination collars against direct visual observations and analysis of video recordings of dairy cows in commercial farm environments. J. Dairy Sci. 98:1750–1758. https://doi.org/10.3168/jds.2014-8565.

Bailey, T., and J. Currin. 2009. Milk production evaluation in first lactation heifers. Accessed Sep. 14, 2020. https://www.pubs.ext.vt.edu/404/404-285/404-285.html.

Barton, K. 2019. MuMIn: Multi-Model Inference. Accessed Mar. 30, 2020. https://cran.r-project.org/package=MuMIn.

Bates, D., M. Mächler, B. M. Bolker, and S. C. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4 67. https://doi.org/10.18637/jss.v067.i01.

Beauchemin, K. A. 2018. Invited review: Current perspectives on eating and rumination activity in dairy cows. J. Dairy Sci. 101:4762–4784. https://doi.org/10.3168/jds.2017-13706.

Braun, U., S. Zürcher, and M. Hässig. 2015. Evaluation of eating and rumination behaviour in 300 cows of three different breeds using a noseband pressure sensor. BMC Vet. Res. 11:231. https://doi.org/10.1186/s12917-015-0549-8.

Calamari, L., N. Soriani, G. Panella, F. Petrera, A. Minuti, and E. Trevisi. 2014. Rumination time around calving: An early signal to detect cows at greater risk of disease. J. Dairy Sci. 97:3635–3647. https://doi.org/10.3168/jds.2013-7709.

De Boever, J. L., J. I. Andries, D. L. De Brabander, B. G. Cottyn, and F. X. Buysse. 1990. Chewing activity of ruminants as a measure of physical structure—A review of factors affecting it. Anim. Feed Sci. Technol. 27:281–291. https://doi.org/10.1016/0377-8401(90)90143-V.

DeVries, T. J., K. A. Beauchemin, F. Dohme, and K. S. Schwartzkopf-Genswein. 2009. Repeated ruminal acidosis challenges in lactating dairy cows at high and low risk for developing acidosis: Feeding, ruminating, and lying behavior. J. Dairy Sci. 92:5067–5078. https://doi.org/10.3168/jds.2009-2102.

Dormann, C. F., J. Elith, S. Bacher, C. Buchmann, G. Carl, G. Carré, J. R. G. Marquéz, B. Gruber, B. Lafourcade, P. J. Leitão, T. Münkemüller, C. Mcclean, P. E. Osborne, B. Reineking, B. Schröder, A. K. Skidmore, D. Zurell, and S. Lautenbach. 2013. Collinearity: A review of methods to deal with it and a simulation study evaluating their performance. Ecography 36:27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x.

Elischer, M. F., M. E. Arceo, E. L. Karcher, and J. M. Siegford. 2013. Validating the accuracy of activity and rumination monitor data from dairy cows housed in a pasture-based automatic milking system. J. Dairy Sci. 96:6412–6422. https://doi.org/10.3168/jds.2013-6790.

Janovick, N. A., and J. K. Drackley. 2010. Prepartum dietary management of energy intake affects postpartum intake and lactation performance by primiparous and multiparous Holstein cows. J. Dairy Sci. 93:3086–3102. https://doi.org/10.3168/jds.2009-2656.

Kaufman, E. I., V. H. Asselstine, S. J. LeBlanc, T. F. Duffield, and T. J. DeVries. 2018. Association of rumination time and health status with milk yield and composition in early-lactation dairy cows. J. Dairy Sci. 101:462–471. https://doi.org/10.3168/jds.2017-12909.

Kaufman, E. I., S. J. LeBlanc, B. W. McBride, T. F. Duffield, and T. J. DeVries. 2016. Association of rumination time with subclinical ketosis in transition dairy cows. J. Dairy Sci. 99:5604–5618. https://doi.org/10.3168/jds.2015-10509.

King, M. T. M., K. M. Dancy, S. J. LeBlanc, E. A. Pajor, and T. J. DeVries. 2017. Deviations in behavior and productivity data before diagnosis of health disorders in cows milked with an automated system. J. Dairy Sci. 100:8358–8371. https://doi.org/10.3168/jds.2017-12723.

King, M. T. M., and T. J. DeVries. 2018. Graduate Student Literature Review: Detecting health disorders using data from automatic milking systems and associated technologies. J. Dairy Sci. 101:8605–8614. https://doi.org/10.3168/jds.2018-14521.

Knowles, J. E., and C. Frederick. 2020. MerTools: Tools for Analyzing Mixed Effect Regression Models. https://cran.univ-paris1.fr/web/packages/mertools/mertools.pdf.

Kononoff, P. J., H. A. Lehman, and A. J. Heinrichs. 2002. Technical note: A comparison of methods used to measure eating and ruminating activity in confined dairy cattle. J. Dairy Sci. 85:1801–1803. https://doi.org/10.3168/jds.S0022-0302(02)74254-9.

Liboreiro, D. N., K. S. Machado, P. R. B. Silva, M. M. Maturana, T. K. Nishimura, A. P. Brandão, M. I. Endres, and R. C. Chebel. 2015. Characterization of peripartum rumination and activity of cows diagnosed with metabolic and uterine diseases. J. Dairy Sci. 98:6812–6827. https://doi.org/10.3168/jds.2014-8947.

Maekawa, M., K. A. Beauchemin, and D. A. Christensen. 2002. Chewing activity, saliva production, and ruminal pH of primiparous and multiparous lactating dairy cows. J. Dairy Sci. 85:1176–1182. https://doi.org/10.3168/jds.S0022-0302(02)74180-5.

Mellado, M., E. Antonio-Chirino, C. Meza-Herrera, F. G. Veliz, J. R. Arevalo, J. Mellado, and A. de Santiago. 2011. Effect of lactation number, year, and season of initiation of lactation on milk yield of cows hormonally induced into lactation and treated with recombinant bovine somatotropin. J. Dairy Sci. 94:4524–4530. https://doi.org/10.3168/jds.2011-4152.

Pahl, C., E. Hartung, K. Mahlkow-Nerge, and A. Haeussermann. 2015. Feeding characteristics and rumination time of dairy cows around estrus. J. Dairy Sci. 98:148–154. https://doi.org/10.3168/jds.2014-8025.

R Core Team. 2020. A language and environment for statistical computing. https://www.r-project.org/.

Reith, S., and S. Hoy. 2012. Relationship between daily rumination time and estrus of dairy cows. J. Dairy Sci. 95:6416–6420. https://doi.org/10.3168/jds.2012-5316.

Schirmann, K., M. A. G. von Keyserlingk, D. M. Weary, D. M. Veira, and W. Heuwieser. 2009. Validation of a system for monitoring rumination in dairy cows. J. Dairy Sci. 92:6052–6055. https://doi.org/10.3168/jds.2009-2361.

Schirmann, K., D. M. Weary, W. Heuwieser, N. Chapinal, R. L. A. Cerri, and M. A. G. von Keyserlingk. 2016. Short communication: Rumination and feeding behaviors differ between healthy and sick dairy cows during the transition period. J. Dairy Sci. 99:9917–9924. https://doi.org/10.3168/jds.2015-10548.

Siewert, J. M., J. A. Salfer, and M. I. Endres. 2019. Milk yield and milking station visits of primiparous versus multiparous cows on automatic milking system farms in the Upper Midwest United States. J. Dairy Sci. 102:3523–3530. https://doi.org/10.3168/jds.2018-15382.

Soriani, N., E. Trevisi, and L. Calamari. 2012. Relationships between rumination time, metabolic conditions, and health status in dairy cows during the transition period. J. Anim. Sci. 90:4544–4554. https://doi.org/10.2527/jas.2011-5064.

Stangaferro, M. L., R. Wijma, L. S. Caixeta, M. A. Al-Abri, and J. O. Giordano. 2016. Use of rumination and activity monitoring for the identification of dairy cows with health disorders: Part I. Metabolic and digestive disorders. J. Dairy Sci. 99:7395–7410. https://doi.org/10.3168/jds.2016-10907.

Stone, A. E., B. W. Jones, C. A. Becker, and J. M. Bewley. 2017. Influence of breed, milk yield, and temperature-humidity index on dairy cow lying time, neck activity, reticulorumen temperature, and rumination behavior. J. Dairy Sci. 100:2395–2403. https://doi.org/10.3168/jds.2016-11607.

Tremblay, M., J. P. Hess, B. M. Christenson, K. K. McIntyre, B. Smink, A. J. van der Kamp, L. G. de Jong, and D. Döpfer. 2016. Factors associated with increased milk production for automatic milking systems. J. Dairy Sci. 99:3824–3837. https://doi.org/10.3168/jds.2015-10152.

Van Den Broeck, J., S.A. Cunningham, R. Eeckels, and K. Herbst. 2005. Data cleaning: Detecting, diagnosing, and editing data abnormalities. PLoS Med. 2:0966–0970. https://doi.org/10.1371/journal.pmed.0020267.

Wickham, H. 2016. Ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag.

Zebeli, Q., M. Tafaj, H. Steingass, B. Metzler, and W. Drochner. 2006. Effects of physically effective fiber on digestive processes and milk fat content in early lactating dairy cows fed total mixed rations. J. Dairy Sci. 89:651–668. https://doi.org/10.3168/jds.S0022-0302(06)72129-4.

ORCIDS

Mateus Peiter https://orcid.org/0000-0003-0031-1805
Hannah N. Phillips https://orcid.org/0000-0003-3059-5765
Marcia I. Endres https://orcid.org/0000-0002-1798-3432