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Rumination time around dry-off relative to the development of diseases in early-lactation cows

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ABSTRACT

Monitoring rumination time (RT) around the time of calving is an effective way of identifying cows at risk of disease in early lactation. However, this only allows for the identification of cows a few days before the onset of clinical signs; thus, effective preventive measures cannot be implemented. Recent research has suggested that biomarkers of immune and metabolic function measured at dry-off (DO) can predict higher disease risk in early lactation. Nevertheless, the extent to which RT around DO is associated with early-lactation disease risk remains unexplored. Thus, the objective of this study was to compare RT in the weeks before and after DO between cows that did and did not experience health disorders in early lactation. For this, we conducted an observational retrospective cohort study utilizing the records available from a large commercial dairy herd in which RT is recorded daily using an automated system. Daily RT from −7 to +14 d relative to DO from 2,258 DO cycles and their respective health records in the first 60 d in milk were used. Differences in RT between animals with and without a disease history were tested with the Student *t*-test with Bonferroni adjustment. Mixed linear regression analyses were performed to assess differences in RT around DO and the association of RT with the occurrence of mastitis, metritis, retained placenta, hyperketonemia, lameness, hypocalcemia, pneumonia, and displaced abomasum. Rumination time decreased abruptly at DO and remained lower for 3 to 4 d compared with the days before DO. On average, cows affected by hyperketonemia and lameness ruminated 9.83 ± 6.40 and 15.00 ± 6.08 min/d less than unaffected cows, respectively. Cows that developed lameness in the first 60 d in milk showed reduced RT from 1 to 3 d following DO compared with cows that were not diagnosed with lameness in early lactation. However, RT around DO was not associated with the occurrence of the other health disorders studied here. Our results demonstrate that DO is a stressful event for dairy cows resulting in decreased RT for several days. Furthermore, the association between RT around DO and some early-lactation diseases suggests that RT could be a useful tool to identify at-risk cows early enough to allow for preventive interventions. Further studies should investigate the diagnostic utility of incorporating RT data early in the dry period in the disease prediction algorithms of rumination sensors.
Key words: activity monitor, dairy cow health, disease prediction, transition period

INTRODUCTION

Dairy cattle are susceptible to increased incidence and severity of metabolic and infectious diseases during the periparturient period (Ingvartsen et al., 2003; Mulligan and Doherty, 2008). Health disorders occurring around the time of calving, such as hyperketonemia (**HYK**), hypocalcemia, mastitis, or metritis, greatly affect the productive efficiency of cows in the ensuing lactation (Wilson et al., 2004; Raboisson et al., 2014; Mann et al., 2019; McArt and Neves, 2020).

During these adverse health events, dairy cows exhibit changes in behavioral patterns of resting, feeding, rumination, physical activity, and social behavior (Dittrich et al., 2019). This so-called sickness behavior is an adaptive response to infection or injury that shows typical characteristics and is caused by the immune and central nervous systems (Johnson, 2002; Tizard, 2008). In recent years, sensors that measure rumination by differentiating specific movements and sounds have been validated for use in dairy cattle (Schirmann et al., 2009) and have been implemented by the dairy industry (Barkema et al., 2015). Reduction in rumination time (**RT**) around calving has been associated with health disorders such as hypocalcemia, mastitis, metritis, HYK, digestive conditions, and lameness (Kaufman et al., 2016; Paudyal et al., 2016, 2018; Schirmann et

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al., 2016; Dittrich et al., 2019; Goff et al., 2020). In addition, RT combined with physical activity data allows for automatically identifying cows with metabolic and digestive disorders and severe cases of mastitis and metritis a few days before the onset of clinical signs (Stangaferro et al., 2016a,b,c).

The pathophysiological processes underlying these diseases, however, might start several weeks before clinical signs are observed. For example, studies have shown differences in the concentration of biomarkers of innate immune function and metabolic status between healthy and diseased early-lactation cows as early as 8 wk before calving (Dervishi et al., 2015, 2016a,b; Zhang et al., 2015, 2016). Moreover, our group identified that the concentration of several inflammatory biomarkers measured at dry-off (**DO**) could be used as predictors of transition diseases at the individual cow and cohort levels (Wisnieski et al., 2019a,b,c). Early identification of dairy cattle at risk for periparturient diseases will allow for the timely implementation of intervention strategies to prevent these health disorders (Wisnieski et al., 2019d). The use of behavioral variables such as RT has been validated to promptly identify sick cows (Stangaferro et al., 2016a,b,c). However, the use of RT to detect periparturient disease as early as DO has not been explored to date. Therefore, the objective of this study was to compare RT around DO between cows with and without a disease diagnosis in early lactation. We hypothesized that cows experiencing disease in early lactation would exhibit reduced RT around DO compared with cows without a disease diagnosis.

MATERIALS AND METHODS

This retrospective observational study was conducted on a large commercial dairy farm located in Clinton County, Michigan. The farm has an average of 4,800 lactating cows with a rolling herd-average milk production of 12,433 kg/cow. Cows are housed in freestall barns with sand bedding and fans for heat abatement. Cows are milked 3 times/d in an 86-point rotary parlor. Exemption from protocol review was granted by the Michigan State University Institutional Animal Care and Use Committee as only electronic records were used. Records were accessed with owners' consent.

Study Population and Data Collection

Rumination time data were collected using an automated rumination monitoring system (Hi-Tag, SCR Engineers Ltd.), which monitors rumination 24 h/d as validated for dairy cows by Schirmann et al. (2009). In the study herd, a random sample of dairy cows is fitted with SCR rumination collars for herd monitoring purposes. The collars determine the total time spent ruminating during each 2-h interval throughout the day. The twelve 2-h intervals each day were added to determine total rumination minutes per day per cow. Only cows with full daily RT data were included for analysis. The RT data from 7 d before to 14 d after DO for all cows dried off between September 2016 and December 2018 were exported from the rumination monitoring system database into a spreadsheet (Excel, Microsoft Corp.) using each cow's lactation as the observational unit because some cows experienced more than 1 DO cycle during the study period.

The information regarding DO date, milk yield recorded by the parlor system, and disease incidence in the first 60 d postcalving was extracted for the selected lactations from the farm's software database (DairyComp 305, Valley Agricultural Software) and incorporated into the spreadsheet. At 7 mo of gestation, cows were confirmed pregnant via rectal palpation and received an *Escherichia coli* vaccine (J-VAC, Boehringer Ingelheim Vetmedica). Subsequently, cows were routinely hoof-trimmed at 8 mo of gestation, and 6 wk before the expected calving date cows were dried off by abrupt cessation of milking and infusion of intramammary antibiotics (Dry-Clox, Boehringer Ingelheim Vetmedica). The day of DO, cows were moved to the far-off dry pen, and moved again to the close-up pen 3 wk before expected calving. Health evaluations and treatments were performed by farm personnel following protocols designed by the herd veterinarian that included the disease definitions outlined in Table 1. After calving, cows spent 1 wk in a designated fresh pen; there, all cows were routinely examined in headlocks by farm staff twice a week, and blood BHB was measured once in every cow between 3 and 7 DIM. After the first week, cows were moved to other pens, which were monitored by farm staff 3 times per day after cows came back from the milking parlor. Cows showing a decreased milk yield $\geq$20% from the previous milking during the first 60 DIM, decreased appetite, or abnormal gait or those flagged by the rumination monitoring system were subjected to a physical exam. The main disease outcomes of interest in this study were mastitis (n = 170), metritis (n = 176), retained placenta (n = 161), uterine disease (retained placenta or metritis; n = 234), HYK (n = 131), lameness (n = 160), and an aggregate outcome (n = 648). An animal was positive for the aggregate outcome if she had 1 or more of the following health events: mastitis, metritis, retained placenta, HYK, lameness, hypocalcemia, pneumonia, or displaced abomasum. The associations of RT with hypocalcemia (n = 18), pneumonia (n =

Table 1. Case definitions for disease outcomes used in this study

Disease	Case definition
Displaced abomasum	A "ping" sound is detected by thumping or tapping the cow's body wall while simultaneously listening with a stethoscope in the area between the 9th and 12th ribs above and below an imaginary line extending from the hip to the elbow on each side of the animal of the abdominal wall.
Hyperketonemia	Concentration of blood BHB >1.2 m*M*, measured with a hand-held device (NovaVet blood ketone and glucose meter; Nova Biomedical Corp.).
Lameness	Abnormal gait assessed through mobility scoring (score ≥3 on a 1-to-5 scale; Sprecher et al., 1997) by farm staff during daily monitoring of pens, followed by assessment by the herd's foot trimmer.
Mastitis	Visually abnormal milk from a quarter identified during manual forestripping in the milking parlor.
Metritis	Abnormal (smelly and watery) vaginal discharge within 21 d of calving.
Milk fever	Muscle weakness, nervousness, muscle shaking, cold ears, and eventually being unable to rise close to calving.
Pneumonia	Altered breathing patterns or respiratory sounds.
Retained placenta	Fetal membranes hanging from the cow's vulva 24 h or more after calving.

26), and displaced abomasum (n = 36) were not tested separately due to low disease counts in these disease categories. For each disease outcome, a cow was considered positive if she had that particular disease, without consideration of the other disease outcomes.

Data Management and Statistical Analyses

Data from a total of 3,287 DO cycles were initially available in the established study period. However, data for a DO cycle were removed from analysis if a disease diagnosis was recorded before calving (n = 6) or if rumination data in one 2-h interval were missing from −7 to 14 d relative to DO (n = 1,023). Thus, rumination data of 2,258 DO cycles from 1,890 cows were used for analysis. This sample size was dictated by the number of full records available and the incidence of the different diseases during the defined study period. The mean (minimum–maximum; interquartile range) dry period length, DIM at DO, and milk yield at DO were 45.8 (10–52; 6) d, 322.3 (261–531; 44) d, and 27.4 (1.4–51.3; 9.1) kg/d, respectively (Table 2).

Stata 14.2 (StataCorp LLC) was used for statistical analyses. Differences in mean RT (min/d) at each individual time point (−7 to 14 d relative to DO) between animals with and without a disease diagnosis were tested in bivariable analyses using Student's *t*-test, with an adjustment for unequal variances. For each health disorder that was significantly associated with RT in the bivariable analyses, a mixed linear regression model was run to test the association of the health disorder with daily RT from −7 to 14 d relative to DO. Covariates included disease status (diagnosis or no diagnosis of disease), lactation number (1, 2, or ≥3), season (spring, summer, fall, or winter), milk yield at DO, and time (day relative to DO). Two-way interactions between disease status and time, disease status and lactation number, disease status and milk yield at DO, and milk yield at DO and lactation number were tested. Backward elimination was performed at an α of 0.05 to select the variables in each final model. However, time, disease status, and a time and disease interaction term were forced in all models to evaluate differences in RT over time in diseased versus nondiseased animals. Random intercepts for year and cow were included to account for an effect of year and the correlation of rumination data collected from the same cow over the lactation cycle, respectively. An autoregressive (2) residual-error structure was chosen given the structure of the data because this residual-error structure can account for stronger correlations between RT collected at time points that are closer together. Normality of residuals was visually checked by assessing histograms and quantile-quantile plots. Heteroskedasticity was visually checked by assessing box plots of the residuals by each categorical variable in the model. A Bonferroni adjustment was used to correct for multiple comparisons between levels of categorical variables.

RESULTS AND DISCUSSION

Average daily RT by day, season, lactation number, and year is shown in Table 2. In bivariable analyses, cows that developed HYK ($P < 0.01$), lameness ($P < 0.01$), metritis ($P = 0.02$), retained placenta ($P < 0.01$), and the aggregate outcome ($P < 0.01$) exhibited significantly reduced daily RT during most or all of the period between −7 and +14 d relative to DO (Table 3). However, only HYK ($P = 0.02$; interaction between HYK and time point) and lameness ($P < 0.01$; main effect of lameness) were significantly associated with RT in the multivariable analysis (Tables 4 and 5). Even though the interaction term between HYK and time was statistically significant, there were no significant differences between cows that developed HYK and those that did not at any of the time points after adjusting for multiple comparisons (Figure 1). However, cows that developed lameness had reduced RT from +1 to +3 d relative to DO compared with animals that did not develop lameness (Figure 2). Previous studies reported reduced RT prepartum in cows that developed HYK postpartum compared with healthy counterparts (Kaufman et al., 2016; Schirmann et al., 2016). However, these studies only monitored RT as early as 10 to 14 d before calving. To our knowledge, this is the first study investigating potential differences in RT around the time of DO between cows that do and do not develop HYK in early lactation. Although significant differences at each individual time point were not detected, the rumination levels among cows that developed HYK were consistently reduced throughout the measurement period. One potential reason for the lack of significant findings could be the lack of statistical power to detect rather small differences in rumination activity between groups. Indeed, even though rumination activity was numerically reduced among the HYK cows compared with non-HYK cows at most of the time points, the wide conference intervals (Figure 1) around the point estimates suggest that we did not achieve the power necessary to find significant differences. A previous study found that greater RT around calving was associated with decreased odds of HYK (Kaufman et al., 2016), but causality remains unexplored. Many metabolic biomarkers associated with metabolic stress in early lactation change in the immediate days following DO (Putman et al., 2018, 2019), suggesting that cows also face metabolic challenges after DO. However, the fact that reduced RT in HYK cows was detected at d −6 and −5 relative to DO indicates that these differences in RT are not necessarily linked to DO but might start already at the end of the lactation. Thus, monitoring RT across the transition from late lactation to the initial stages of mammary gland involution may contribute to the identification of cows at risk of

Table 2. Summary statistics for milk yield at dry-off and rumination by season, year, time point (−7 to 14 d relative to dry-off), and lactation number (2,258 unique dry-off cycles among 1,890 animals)

		Milk yield at dry-off (kg/d)		Rumination time (min/d)	
Item	n	Mean	SD	Mean	SD
Lactation number					
1	1,184	28.8	6.17	530.3	77.1
2	697	26.6	7.98	515.9	78.3
≥3	377	24.7	7.64	511.0	76.6
Season					
Spring	663	27.8	6.47	526.3	75.4
Summer	472	29.0	7.44	533.8	81.1
Fall	288	27.1	7.73	515.7	80.3
Winter	835	26.3	7.23	515.7	76.0
Year					
2016	102	24.3	7.06	552.5	73.8
2017	1,302	27.9	7.54	526.6	78.4
2018	854	27.0	6.53	513.0	75.9
Day relative to dry-off					
−7		—		507.1	66.7
−6		—		507.9	65.9
−5		—		510.4	66.6
−4		—		508.5	66.3
−3		—		507.3	67.5
−2		—		510.9	66.4
−1		—		508.6	66.8
0		—		459.6	72.6
1		—		496.0	99.2
2		—		495.9	98.9
3		—		522.1	96.0
4		—		529.2	86.6
5		—		543.9	78.6
6		—		549.0	72.6
7		—		536.4	70.2
8		—		534.7	70.3
9		—		537.1	72.7
10		—		545.0	69.2
11		—		540.6	68.8
12		—		551.7	65.4
13		—		552.3	66.7
14		—		543.6	65.4

Table 3. Mean (SD) daily rumination time (min) by disease status and time point (−7 to 14 d relative to dry-off) in a large sample of dairy cattle (2,258 unique dry-off cycles among 1,890 animals)

	Hyperketonemia		Lameness		Mastitis		Metritis		Retained placenta		Uterine diseases[1]		Aggregate outcome[2]	
Day	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
n	131	2,127	160	2,098	170	2,088	176	2,082	161	2,097	234	2,024	648	1,610
−7	487.5 (71.2)*	508.3 (66.2)	488.7 (73.1)*	508.5 (65.9)	512.4 (62.2)	506.7 (67.0)	503.3 (73.1)	507.4 (66.1)	511.0 (65.3)	506.8 (66.8)	503.4 (69.3)	507.5 (66.3)	501.3 (69.0)*	509.5 (65.6)
−6	485.3 (64.1)*	509.3 (65.8)	496.5 (73.3)*	508.8 (65.3)	511.1 (57.2)	507.6 (66.6)	502.7 (74.9)	508.3 (65.1)	512.2 (65.9)	507.6 (65.9)	502.1 (72.1)	508.6 (65.2)	501.1 (68.1)*	510.4 (64.9)
−5	485.6 (65.0)*	511.9 (66.4)	495.8 (68.7)*	511.5 (66.3)	517.1 (62.0)	509.8 (67.0)	505.8 (73.5)	510.8 (66.0)	511.5 (59.7)	510.3 (67.1)	505.1 (69.5)	511.0 (66.3)	504.0 (68.5)*	512.9 (65.7)
−4	488.7 (71.3)*	509.7 (65.8)	491.5 (70.7)*	509.8 (65.7)	510.0 (62.0)	508.3 (66.6)	509.0 (69.2)	508.4 (66.0)	513.4 (59.4)	508.1 (66.7)	508.0 (65.5)	508.5 (66.4)	503.3 (66.2)*	510.6 (66.2)
−3	490.6 (67.0)*	508.3 (67.3)	488.9 (78.0)*	508.7 (66.5)	509.4 (61.1)	507.1 (68.0)	505.7 (69.4)	507.4 (67.4)	515.3 (60.9)	506.7 (68.0)	505.7 (65.7)	507.5 (67.7)	501.1 (68.7)*	509.8 (66.9)
−2	492.4 (66.2)*	512.1 (66.3)	490.1 (81.6)*	512.5 (64.9)	509.1 (62.4)	511.1 (66.7)	507.4 (69.1)	511.2 (66.2)	518.3 (63.7)	510.4 (66.5)	509.7 (66.1)	511.1 (66.5)	503.7 (69.1)*	513.8 (65.1)
−1	493.5 (65.6)*	509.5 (66.8)	491.6 (83.8)*	509.9 (65.2)	507.9 (61.5)	508.6 (67.3)	503.9 (64.3)	509.0 (67.0)	510.4 (62.7)	508.4 (67.1)	502.8 (63.4)	509.3 (67.2)	502.3 (69.6)*	511.1 (65.5)
0	438.2 (71.4)*	461.0 (72.4)	449.6 (84.2)	460.4 (71.6)	457.0 (69.0)	459.8 (72.9)	451.2 (74.5)	460.3 (72.4)	459.0 (71.8)	459.7 (72.6)	453.7 (71.2)	460.3 (72.7)	454.1 (72.5)*	461.8 (72.5)
1	486.2 (95.7)	496.6 (99.4)	472.2 (93.3)*	497.8 (99.4)	498.7 (96.6)	495.8 (99.4)	498.0 (108.9)	495.8 (98.4)	497.6 (101.8)	495.9 (99.0)	495.0 (101.6)	496.1 (99.0)	489.4 (97.8)*	498.7 (99.7)
2	484.4 (93.6)	496.6 (99.2)	473.0 (102.7)*	497.6 (98.4)	485.8 (95.5)	496.7 (99.2)	498.3 (95.7)	495.7 (99.2)	505.8 (86.2)	495.1 (99.8)	498.4 (92.3)	495.6 (99.7)	486.5 (96.0)*	499.6 (99.8)
3	493.9 (96.7)*	523.8 (95.8)	500.2 (100.1)*	523.7 (95.5)	514.5 (94.6)	522.7 (96.2)	521.6 (93.4)	522.1 (96.3)	527.2 (87.5)	521.7 (96.7)	521.5 (90.0)	522.1 (96.7)	511.2 (95.1)*	526.4 (96.1)
4	504.6 (88.1)*	530.7 (86.3)	510.8 (92.3)*	530.6 (86.0)	526.6 (85.5)	529.4 (86.7)	527.6 (83.9)	529.3 (86.9)	532.0 (76.8)	528.9 (87.3)	527.4 (81.9)	529.4 (87.2)	518.9 (85.2)*	533.3 (86.9)
5	525.7 (80.5)*	545.0 (78.4)	524.9 (88.5)*	545.3 (77.6)	537.9 (76.7)	544.4 (78.7)	541.5 (74.9)	544.1 (78.9)	543.7 (72.8)	543.9 (79.0)	540.9 (73.1)	544.2 (79.2)	534.0 (78.4)*	547.8 (78.3)
6	525.7 (70.0)*	550.4 (72.5)	531.1 (74.4)*	550.3 (72.3)	544.2 (61.0)	549.3 (73.4)	546.7 (69.8)	549.1 (72.8)	554.7 (69.9)	548.5 (72.8)	549.7 (68.9)	549.7 (73.0)	540.2 (70.0)*	552.5 (73.3)
7	529.5 (67.4)	536.8 (70.4)	515.8 (78.9)*	538.0 (69.7)	532.7 (63.8)	536.7 (70.7)	537.8 (70.1)	536.3 (70.3)	544.8 (69.8)	535.8 (70.2)	538.9 (67.5)	536.1 (70.6)	530.2 (69.2)*	538.9 (70.5)
8	527.3 (67.8)	535.1 (70.4)	518.8 (66.7)*	536.0 (70.4)	529.8 (63.6)	535.1 (70.8)	531.3 (74.8)	535.0 (69.9)	538.5 (71.5)	534.4 (70.2)	533.4 (71.8)	534.8 (70.1)	528.6 (68.6)*	537.1 (70.8)
9	522.8 (71.3)*	538.0 (72.8)	522.8 (74.9)*	538.2 (72.5)	530.2 (71.7)	537.7 (72.8)	534.7 (72.6)	537.3 (72.8)	542.5 (70.8)	536.7 (72.9)	535.9 (70.2)	537.2 (73.1)	530.4 (71.9)*	539.8 (72.9)
10	531.5 (68.1)*	545.8 (69.2)	526.5 (69.5)*	546.4 (69.0)	542.2 (71.7)	545.2 (69.0)	538.4 (73.3)	545.5 (68.8)	547.2 (68.1)	544.8 (69.3)	540.3 (71.5)	545.5 (68.9)	537.8 (70.7)*	547.8 (68.3)
11	532.7 (72.9)	541.1 (68.6)	524.9 (63.5)*	541.8 (69.1)	540.1 (66.2)	540.6 (69.1)	534.3 (79.2)	541.1 (67.9)	543.6 (71.6)	540.4 (68.6)	537.5 (75.1)	540.9 (68.1)	534.8 (70.5)*	542.9 (68.0)
12	541.0 (70.5)	552.3 (65.0)	537.0 (65.5)*	552.8 (65.2)	551.0 (60.7)	551.7 (65.7)	543.5 (71.6)	552.4 (64.8)	556.6 (68.9)	551.3 (65.1)	548.7 (69.3)	552.0 (64.9)	546.2 (66.6)*	553.9 (64.7)
13	541.1 (63.1)*	553.0 (66.8)	540.2 (62.3)*	553.3 (66.9)	546.3 (62.6)	552.8 (67.0)	549.0 (73.9)	552.6 (66.0)	560.2 (71.5)	551.7 (66.3)	552.2 (72.8)	552.4 (65.9)	546.4 (67.2)*	554.7 (66.3)
14	537.7 (62.1)	544.0 (65.6)	527.4 (64.2)*	544.9 (65.3)	537.6 (61.2)	544.1 (65.7)	542.4 (73.2)	543.7 (64.7)	545.7 (67.1)	543.5 (65.3)	543.1 (70.8)	543.7 (64.8)	537.7 (66.3)*	546.0 (64.9)
Overall	506.6 (78.1)*	523.6 (77.7)	505.4 (64.2)*	523.9 (77.4)	520.5 (73.7)	522.8 (78.2)	519.7 (80.3)*	522.9 (77.6)	526.9 (75.3)*	522.3 (78.0)	520.6 (77.7)	522.9 (77.8)	515.6 (77.9)*	525.4 (77.6)

[1]Included both metritis and retained placenta.

[2]One or more of the following health events: mastitis, metritis, retained placenta, hyperketonemia, lameness, hypocalcemia, pneumonia, and displaced abomasum.

*Daily rumination significantly ($P < 0.05$) different from the comparison group (no disease). Calculated using t-test adjusted for unequal variances.

HYK in early lactation. The milk yield at DO was also similar between HYK and non-HYK cows, with a mean (SD) production of 24.9 (6.47) and 27.5 (7.21) kg/d, respectively. Thus, it is unlikely that the differences observed between HYK and non-HYK cows are attributed to changes in RT associated with the amount of milk being produced when dried off.

First-parity cows (n = 74) accounted for the majority of observed lameness cases, followed by cows in second parity (n = 62) and third or greater parity (n = 24). Thus, it is unlikely that the differences observed between lame and nonlame cows are attributed to an association between parity and lameness status because first-parity cows showed greater RT than the other parity groups. Likewise, the milk yield at DO was similar between lame (mean ± SD: 26.0 ± 6.4 kg/d) and nonlame (27.5 ± 7.08 kg/d) cows, suggesting that the differences observed in RT are not attributed to an association between milk yield at DO and lameness status. There is mixed evidence in the literature for the effect of lameness on RT. Some studies found no association between lameness and RT (Walker et al., 2008; Thorup et al., 2016), whereas Van Hertem et al. (2013) found reduced RT starting 6 d before lameness diagnosis. Some research has shown that lameness might be triggered during the dry period despite the clinical signs being observed in early lactation (Proudfoot et al., 2010; Lim et al., 2015). During the study period, 85.4% of the cases of lameness recorded in the farm were related to claw horn disruption lesions. Claw horn grows at a relatively slow rate (Prentice, 1973). Thus, a considerable amount of time from injury to the stratum

Table 4. Mixed linear regression analyses to assess the association of hyperketonemia and other factors with daily rumination time (average min/d) in a large sample of dairy cattle (2,258 unique dry-off cycles among 1,890 animals)[1]

Variable	Coefficient	SE	*z*-value	*P*-value
Hyperketonemia[2]	−9.83	6.40	−1.54	0.12
Milk production at dry-off	1.56	0.14	11.37	<0.01
Lactation number				<0.01
1	Referent	—	—	<0.01
2	−11.33	2.19	−5.17	<0.01
≥3	−11.35	2.73	−4.15	<0.01
Day relative to dry-off				<0.01
−7	Referent	—	—	—
−6	0.95	1.45	0.66	0.51
−5	3.57	1.56	2.29	0.02
−4	1.36	1.69	0.80	0.42
−3	−0.01	1.75	−0.01	0.99
−2	3.75	1.78	2.10	0.04
−1	1.18	1.80	0.66	0.51
0	−47.38	1.81	−26.12	<0.01
1	−11.71	1.82	−6.43	<0.01
2	−11.74	1.82	−6.43	<0.01
3	−15.47	1.83	8.47	<0.01
4	22.35	1.83	12.22	<0.01
5	36.66	1.83	20.05	<0.01
6	42.06	1.83	22.99	<0.01
7	28.50	1.83	15.58	<0.01
8	26.82	1.83	14.66	<0.01
9	29.64	1.83	16.20	<0.01
10	37.45	1.83	20.47	<0.01
11	32.75	1.83	17.89	<0.01
12	44.01	1.83	24.05	<0.01
13	44.70	1.83	24.43	<0.01
14	35.68	1.83	19.50	<0.01
Season				<0.01
Spring	Referent	—	—	—
Summer	−1.58	2.91	−0.54	0.59
Fall	−23.22	3.47	−6.70	<0.01
Winter	−12.84	2.39	−5.38	<0.01
Hyperketonemia and time point interaction term	See Figure 1	—	—	0.02
Intercept	489.86	13.54	36.19	<0.01

[1]Random intercept variance estimates: year = 480.14 (95% CI: 92.23–2,499.56); animal = 1,585.03 (95% CI: 1,469.63–1,709.48). Model included an autoregressive (2) residual covariance structure accounting for heterogeneous variances by disease status.

[2]Referent = cows without hyperketonemia.

basalis of the corium epidermal tissues to clinical signs of lameness is expected. Therefore, it is possible that the reduced RT observed in cows that developed lameness postpartum is due to subclinical lesions that do not result in abnormal gait until after calving. Hence, monitoring RT during the dry period could be used to identify and examine cows at risk for lameness before the onset of clinical signs.

A decrease in RT associated with the development of hypocalcemia, metritis, displaced abomasum, and severe cases of mastitis was previously documented (Fogsgaard et al., 2012; Stangaferro et al., 2016a,b,c; Steensels et al., 2017; King et al., 2018; Paudyal et al., 2018; Goff et al., 2020). However, these studies monitored RT only around the time of calving, and the decrease in RT may occur just closer to the onset of clinical signs in these diseases. For example, low Ca concentrations are associated with low RT (Goff et al., 2020), but the large deficit of Ca for colostrum and milk production does not take place until around parturition (Mann et al., 2019). Similarly, cows with coliform mastitis exhibit low RT (Fogsgaard et al., 2012). This drop in rumination, however, is attributed to the severe inflammatory response, including sudden shock and sepsis, that characterizes intramammary infections caused by *E. coli* (Burvenich et al., 2007), and likely occurs shortly before clinical signs are observed. In fact, Stangaferro et al. (2016b) detected a decrease in RT associated with clinical mastitis just 1 d before clinical diagnosis. Thus, we speculate that the lack of associations between RT at DO and the occurrence of these diseases in our study is attributed to RT decreasing shortly before the onset of clinical signs.

Time patterns of RT relative to DO were also identified in multivariable analysis (Tables 4 and 5). Rumination time remained steady in the 7 d before DO, sharply

Table 5. Mixed linear regression analyses to assess the association of lameness and other factors with daily rumination (average min/d) in a large sample of dairy cattle (2,258 unique dry-off cycles among 1,890 animals)[1]

Variable	Coefficient	SE	*z*-value	*P*-value
Lameness[2]	−15.00	6.08	−2.47	0.01
Milk production at dry-off	1.54	0.14	11.25	<0.01
Lactation number				<0.01
1	Referent	—	—	<0.01
2	−11.31	2.18	−5.19	<0.01
≥3	−11.84	2.72	−4.36	<0.01
Day relative to dry-off				<0.01
−7	Referent	—	—	—
−6	0.23	1.45	0.16	0.87
−5	2.96	1.56	1.90	0.06
−4	1.24	1.70	0.73	0.46
−3	0.16	1.75	0.09	0.93
−2	4.00	1.79	2.24	0.03
−1	1.36	1.80	0.75	0.45
0	−48.12	1.82	−26.49	<0.01
1	−10.69	1.82	−5.86	<0.01
2	−10.89	1.83	−5.96	<0.01
3	15.21	1.83	8.32	<0.01
4	22.04	1.83	12.04	<0.01
5	36.80	1.83	20.10	<0.01
6	41.80	1.83	22.82	<0.01
7	29.45	1.83	16.08	<0.01
8	27.39	1.83	14.95	<0.01
9	29.66	1.83	16.19	<0.01
10	37.84	1.83	20.65	<0.01
11	33.26	1.83	18.15	<0.01
12	44.29	1.83	24.17	<0.01
13	44.74	1.83	24.42	<0.01
14	36.36	1.83	19.85	<0.01
Season				<0.01
Spring	Referent	—	—	—
Summer	−0.96	2.91	−0.33	0.74
Fall	−22.48	3.46	−6.50	<0.01
Winter	−12.24	2.38	−5.14	<0.01
Lameness and time point interaction term	See Figure 2	—	—	0.81
Intercept	490.13	13.28	36.91	<0.01

[1]Random intercept variance estimates: year = 459.911 (95% CI: 88.32–2,395.70); animal = 1,573.10 (95% CI: 1,458.31–1,696.92). Model included an autoregressive (2) residual covariance structure.

[2]Referent = cows without lameness.

decreased on the day of DO, and remained lower than before DO for 3 to 4 d. To our knowledge, only one other study monitored RT around the time of DO, reporting an increase in RT after DO (Mezzetti et al., 2020). However, this previous study reported RT only at weekly intervals relative to DO. Thus, it is possible that the drop in RT observed in our study shortly after DO was not detected in their study. Compared with before DO, RT from 3 to 4 d after DO onward was also higher in our data set. This finding further supports the contention that the time of DO is a stressful event for dairy cows (Zobel et al., 2015). For example, abrupt cessation of milking at DO could induce pain associated with increased udder pressure (Silanikove et al., 2013) and trigger an elevation of glucocorticoid concentrations (Bertulat et al., 2013). Dry-off allows the development of the mammary gland and the turnover of its secretory tissue (Oliver and Sordillo, 1988) and is critical to maximizing milk production and udder health in the ensuing lactation (Dufour et al., 2011). Hence, a dry period is now standard on most dairy farms in the United States, with 73.6% of operations using the abrupt milking cessation method for DO (NAHMS, 2016). Recent studies have explored methods to decrease milk production at DO as a way to facilitate mammary gland involution (Boutinaud et al., 2016, 2017). To our knowledge, there are no reports of the US average daily milk yield at DO. However, previous single-farm studies reported an average of 22.7 kg/d (Rajala-Schultz et al., 2018) and 24.7 kg/d (Chapinal et al., 2014), in line with the 27.2 kg/d reported in this study. Thus, additional studies are needed to assess the effect on welfare indicators in animals producing substantial amounts of milk at the time of DO.

In addition to changes in the mammary gland, cows face other potentially stressful events at the time of DO that likely contribute to the observed drop in RT in the days following DO. Dried-off cows experience sudden changes in diet composition and social structure due to regrouping, which can also induce stress that results in alterations of behavioral variables (von Keyserlingk et al., 2008). Due to the study design, however, it is not possible to differentiate the potential effects of sudden milk cessation from those of nutrition and social changes around DO. Nevertheless, our results indicate that the challenges faced by dairy cows at DO reduce RT. Given that reduced RT around the time of DO was associated with the development of HYK and lame-

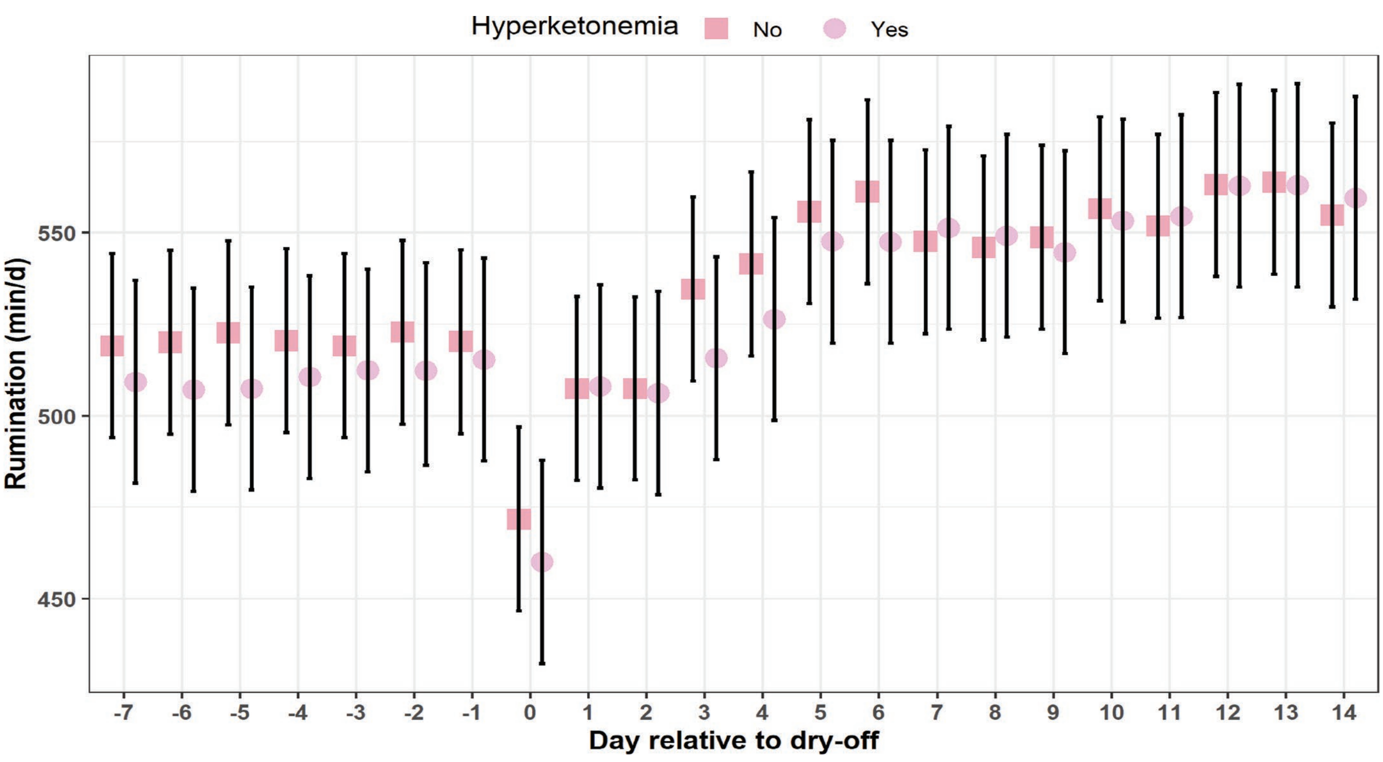

Figure 1. Least squares means estimates and 95% CI from a model comparing rumination time (average min/d), measured from −7 to 14 d relative to dry-off, between cattle that developed hyperketonemia and cattle that did not develop hyperketonemia in early lactation (2,258 unique dry-off cycles among 1,890 animals). Error bars represent the 95% CI. There were no significant differences between hyperketonemia groups within time point after adjustment for multiple comparisons with the Bonferroni correction.

ness postpartum, it is possible that information about how cows adapt to the transition from the lactating to the nonlactating stage could be an indicator of their capacity to adapt to the changes associated with calving satisfactorily. Interestingly, when comparing RT at each individual time point, only differences in RT in the few days after DO in future lame cows were found. There were no differences in future HYK cows. Only 11 lactation cycles resulted in both HYK and lameness; therefore, there was little overlap in the occurrence of these conditions. We speculate that these differences in findings might be attributed to the different modes of pathogenesis of both conditions. Thus, further research into the relationship between the adaptation to the nonlactating stage and its relationship with early-lactation disorders is warranted.

Parity and season were also associated with differences in RT (Tables 4 and 5), with RT decreasing as lactation number increased, and shorter daily RT being observed in fall and winter compared with summer and spring. No previous study compared RT around the time of DO among parity groups or seasons. However, the negative association between lactation number and RT might be explained by the negative relationship between DMI and RT in dry cows (Schirmann et al., 2012) because DMI increases with parity (Azizi et al., 2009). Another potential explanation for higher parity cows showing reduced RT is the relationship between RT and milk yield at DO. Milk yield at DO significantly ($P < 0.01$) decreased with parity; first-parity cows had the highest milk yield (mean ± SEM; 28.8 ± 0.2 kg/d), followed by second-parity cows (26.6 ± 0.3 kg/d) and cows in third parity or greater (24.7 ± 0.4 kg/d). Thus, it is also possible that higher parity cows, being dried off with lower daily yields, had lower nutritional demands at DO that resulted in lower RT.

Paudyal et al. (2016) found that RT before calving (d −14 to −1) was reduced during the hot season in Florida (June 1 to September 30). Heat stress is known to decrease RT in lactating cows (Soriani et al., 2013). Nevertheless, the number of heat stress days per year in Michigan is markedly lower than in Florida (Laporta et al., 2020), which could justify why there was not a marked reduction in RT during the warm seasons in our results.

A limitation of this observational study is the inability to determine cause–effect relationships between RT around DO and the development of certain diseases in early lactation. Thus, it remains unclear whether (1) cows experience certain diseases in early lactation due

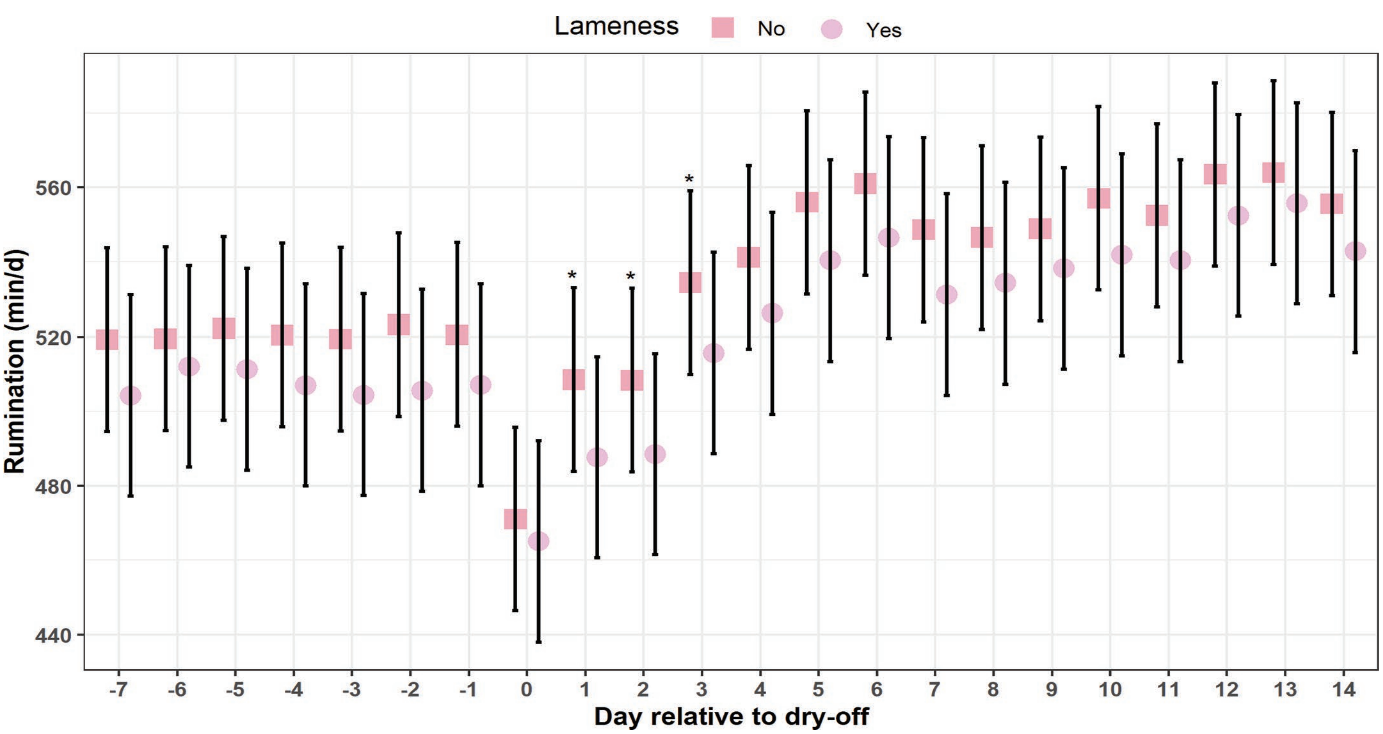

Figure 2. Least squares means estimates and 95% CI from a model comparing rumination time (average min/d), measured from −7 to 14 d relative to dry-off, between cattle that developed lameness and cattle that did not develop lameness in early lactation (2,258 unique lactation cycles among 1,890 animals). Error bars represent the 95% CI. Asterisk indicates significant difference ($P < 0.05$) compared with the lameness group within time point. P-values were adjusted using the Bonferroni correction for multiple comparisons.

to lower RT around the time of DO, (2) cows show lower RT at DO because they are already subclinically sick, or (3) other variables influence RT at DO and disease occurrence in early lactation. Also, not considering the occurrence of other health disorders during a window of time around the health disorder of interest is a weakness of this study because some early-lactation cows develop more than 1 disorder within a short period of time. Hence, it is possible that cows that develop more than 1 disorder could have different physiology and behavior and, therefore, potentially different RT patterns than cows that develop a single disorder. Nevertheless, the associations documented in this study could still be used for early identification of cows at a higher risk of disease in early lactation using automatic sensors.

CONCLUSIONS

Dry-off is a stressful moment for dairy cattle that reduces RT for 3 to 4 d. Furthermore, reduced RT in the weeks around DO has been associated with the occurrence of HYK and lameness postpartum. Thus, RT around the time of DO could potentially be used by sensors to predict cows at risk of health disorders in early lactation. This would allow time to implement proactive interventions in cows that are projected to have high disease incidence. Further studies should investigate the diagnostic utility of incorporating RT data early in the dry period in the disease prediction algorithms of rumination sensors.

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