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Evaluation of sensor-based health monitoring in dairy cows: Exploiting rumination times for health alerts around parturition

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ABSTRACT

The use of sensor-based measures of rumination time as a parameter for early disease detection has received a lot of attention in scientific research. This study aimed to assess the accuracy of health alerts triggered by a sensor-based accelerometer system within 2 different management strategies on a commercial dairy farm. Multiparous Holstein cows were enrolled during the dry-off period and randomly allocated to conventional (CON) or sensor-based (SEN) management groups at calving. All cows were monitored for disorders for a minimum of 10 DIM following standardized operating procedures (SOP). The CON group (n = 199) followed an established monitoring protocol on the farm. The health alerts of this group were not available during the study but were later included in the analysis. The SEN group (n = 197) was only investigated when the sensor system triggered a health alert, and a more intensive monitoring approach was implemented according to the SOP. To analyze the efficiency of the health alerts in detecting disorders, the sensitivity (SE) and specificity (SP) of health alerts were determined for the CON group. In addition, all cows were divided into 3 subgroups based on their health status and the status of the health alerts in order to retrospectively compare the course of rumination time. Most health alerts (87%, n = 217) occurred on DIM 1. For the confirmation of diagnoses, health alerts showed SE and SP levels of 71% and 47% for CON cows. In SEN cows, SE of 71% and 75% and SP of 48% and 43% were found for the detection of ketosis and hypocalcemia, respectively. The rumination time of the subgroups was affected by DIM and the interaction between DIM and the status of health alert and health condition.

Key words: health alert, accelerometer, herd health management, rumination time

INTRODUCTION

Today's dairy farmers are faced with a variety of demands in managing their farms. On one hand, herd sizes are increasing to withstand the economic pressure in agriculture, but recruiting qualified personnel is a challenge, limiting the labor available per cow (Douphrate et al., 2013; Charlton and Kostandini, 2021). On the other hand, society has increasing demands on animal welfare, which is mainly seen as the responsibility of farmers (Clark et al., 2019). To meet these economic and social demands, efficient approaches to individual and herd health management are needed.

In particular, the period around calving is considered to be critical and important for cow health and the performance of the cow's subsequent lactation, and it would benefit from a targeted herd health management approach (LeBlanc, 2010; Caixeta and Omontese, 2021). During this period, the incidence of clinical and subclinical diseases is approximately 35% and 60%, respectively (LeBlanc, 2010). Accelerating the diagnosis of health issues, reducing morbidity, maximizing milk yield, and preparing the cow for the first service are, therefore, the main objectives (Silva et al., 2021). Consequently, poor management is resulting in economic losses (Kristula et al., 2001). Health screening protocols are often established to improve management, but they vary widely in intensity and quality (Heuwieser et al., 2010; Espadamala et al., 2016). The implementation of standardized operating procedures (**SOP**) is therefore a way to systematically and comparably assess the health status of cows (LeBlanc, 2010; Espadamala et al., 2016). Nevertheless,

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The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-24. Nonstandard abbreviations are available in the Notes.

the protocols for health monitoring are time consuming and may possibly negatively affect the cow's natural behavior, as she must be restrained for examination and treatment procedures, e.g., in a headlock or palpation rail. As the use of sensor technologies becomes more popular among farmers, continuous and automated monitoring of cows could improve the efficiency of fresh cow management protocols (Hostiou et al., 2017; Vieira et al., 2021).

Accelerometer-based sensor technologies that relate behavioral patterns such as rumination time and activity levels to postpartum health disorders have previously been the subject of scientific research (Calamari et al., 2014; Schirmann et al., 2016; Gusterer et al., 2020). Farmers can choose from a wide range of sensor systems, which have been evaluated to a greater or lesser extent (Stygar et al., 2021). Moreover, some of these systems provide health alerts based on machine learning algorithms (Stygar et al., 2021). Artificial intelligence is able to interpret changes in measured behavioral patterns, such as rumination time or activity levels, as health alerts. This could help farmers to focus on animals with suspected disease rather than screening the entire group of cows for disorders (Eckelkamp and Bewley, 2020). The use of health alerts may also contribute to easier detection of subclinical disease after parturition, as, for example, subclinical ketosis and hypocalcemia have been associated with reduced rumination time (Liboreiro et al., 2015; Kaufman et al., 2016). However, these sensor-based management concepts require accurate health alerts in terms of sensitivity and specificity. Factors that might influence the accuracy of sensor-based health alerts in the fresh cow period are the change in cow behavior patterns around calving and the quality of animal observations by the investigators leading to diagnoses. At calving, an increase in animal activity and a decrease in rumination time have been reported in several studies (Borchers et al., 2017; Hut et al., 2022; Antanaitis et al., 2023). Because disorders are likely to occur during the fresh cow period shortly after parturition including changes in rumination and activity levels (Gusterer et al., 2020), health alerts need to be able to distinguish behavioral changes caused from either calving or disease. In addition, the intensity of monitoring procedures could have an impact on the outcome of diagnoses. A more intensive examination strategy in a commercial setting associated with health alerts could lead to a higher number of true positive diagnoses. To evaluate the accuracy of health alerts, it is necessary to compare the information in health alerts with diagnoses of investigators, supported by laboratory results as a reference standard.

In terms of accuracy, Stangaferro et al. (2016a) reported an overall good sensitivity for health alerts based on a health index score of rumination time and activity level, but did not present the corresponding specificities. Similarly, Silva et al. (2021) did not provide information on the presence of false positive health alerts in their study on the effect of adding sensor-based health alerts to health screening management. Only Paudyal et al. (2018) presented the sensitivities and specificities of health alert models based on raw rumination time data during early lactation. For this reason, an evaluation of the accuracy of sensor systems generating health alerts based on rumination time during the period around calving is lacking.

Our study aims to evaluate 2 different health management strategies for frequent disorders around calving in relation to sensor-based health alerts. The first strategy (conventional; **CON**), regardless of health alerts, refers to the examination of a cow's health status based on clinical signs, without relying on sensor data, and has already been implemented on a commercial dairy farm. For this strategy, health alerts were not used, but will be retrospectively compared with diagnosed diseases to evaluate the sensitivity and specificity of health alerts. The second strategy (sensor-based; **SEN**) determined whether more intensive screening (in which only cows with health alerts were examined) changes the ratio of health alerts to diagnoses recorded. Furthermore, the sensitivity and specificity of health alerts regarding hypocalcemia and ketosis was evaluated for this group. In addition, the course of rumination was retrospectively analyzed for all cows with respect to their status of health alerts and diagnoses.

MATERIALS AND METHODS

All study procedures were approved by the State Office of Agriculture, Food Safety and Fisheries Mecklenburg-Vorpommern, Germany (7221.3-2-013/21), and noted by the Ethics Committee of the University of Veterinary Medicine, Vienna. The study was conducted between June 2020 and November 2021 on a conventional dairy farm in northern Germany with approximately 1,900 Holstein-Friesian cows.

Animals, Housing, and Feeding

The study included cows in the dry-off and transition periods (from 60 ± 3 d before expected calving until a maximum of 16 d postpartum), that were fitted with an accelerometer-based ear tag to measure rumination time and generate health alerts. Cows entered the study at the time of drying off and were housed in a group of approximately 200 animals in a freestall barn with cubicles filled with recycled solid manure as bedding material. The subsequent dry period was divided into a far-off period (60 ± 3 d to 21 ± 3 d before expected calving) and a close-up period (21 ± 3 d before expected calving). Once a week, cows entering the close-up period were moved

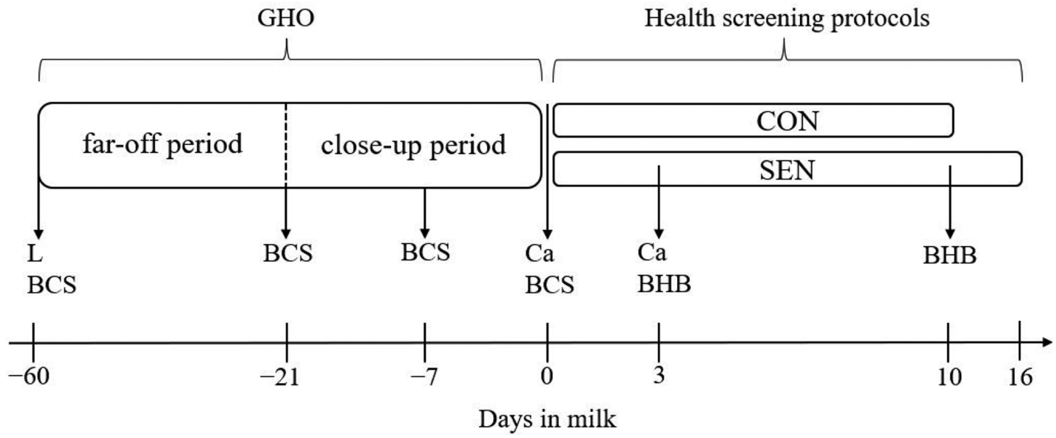

Figure 1. Schematic representation of the study design. Cows were enrolled at dry-off −60 ± 3 d before expected calving date. The cows selected for the study had a BCS within the range of 2.0 to 4.0 according to Edmonson et al. (1989) and a lameness score (L) of less than 4 according to Sprecher et al. (1997). During the dry-off period, the cows received daily visual general health observations (GHO), which included the observation of lameness and discomfort, as well as multiple checks for BCS (−21 ± 3, −7 ± 3 d prepartum, and at calving). At calving, the cows were paired and randomly assigned to either a conventional group (CON) or a study group (SEN). From DIM 1, the CON group underwent a health screening protocol without available health alerts for the investigator, whereas the SEN group underwent a health screening protocol based on the occurrence of health alerts. Additionally, at calving, the CON group received 120 mL of calcium s.c. Furthermore, during the first 10 DIM, the blood level of SEN cows was routinely checked for calcium concentration on DIM 0 and 3 and BHB on DIM 3 and 10.

to the special needs barn. This barn provided different areas, with (1) cubicles equipped with recycled solid manure, (2) group pens for a maximum of 5 cows with straw bedding, and (3) cubicles with straw-chalk bedding. Area 1 was used for cows in the close-up phase, while area 2 was used for calving and area 3 for the postcalving period. The combination of these different areas in one barn provided the opportunity for intensive and close monitoring of the cows during this sensitive period. Animals showing signs of calving (restlessness, appearance of the allantoic sac through the vulva) or cows that were close to the expected calving date (i.e., within 3 d before expected calving) were moved to the calving area. After calving, animals of both groups were transferred to area 3 (generally until 10 DIM; or until an animal was considered to be healthy). Cows in the fresh cow pen were milked twice daily (0530 and 1730 h) in a 12-side-by-side parlor. During the rest of lactation, animals were divided into groups of approximately 200 cows based on reproductive status, parity number, and SCC. In 2022, the average ECM yield of the conventional farm (based on 4% butterfat and 3.4% protein) over 305 d was 12,063 kg per cow. The cows were fed a TMR once a day (at 0430 h), which was pushed up every 4 h. The ration consisted mainly of corn silage, grass silage, concentrates, and supplements, which varied during the different lactation periods. Cows had ad libitum access to fresh water.

Dry-Off Period Until Calving. Multiparous cows were selected at the start of the dry-off period and had to meet the criteria of sound health, as defined by a lameness score <4 according to Sprecher et al. (1997) and a BCS within a range of 2.0 to 4.0 according to Edmonson et al. (1989). From dry-off until the day of calving (i.e., DIM 0), all study animals were visually inspected once a day by a veterinarian for signs of discomfort and lameness (general health observation), and the BCS was checked on d 21 ± 3 antepartum (**a.p.**), d 7 ± 3 a.p., and at the day of calving. Cows showing a lameness score ≥4 or discomfort at any time before parturition were excluded from the study if treatment was required. In addition, cows with dystocia, twins, cesarean section, or fetotomy were also excluded from the study.

Before the start of the study, the random assignment of groups was designed using the Excel random tool (MS Excel, Microsoft Excel, version 2012), whereas the allocation of the cows was done according to the date and time of calving and number of lactations. The cows in each pair were then randomly assigned to the SEN group (intensive health monitoring protocol based on the occurrence of sensor-based health alerts) and the CON group (conventional health monitoring protocol, which was already initiated on the farm). A systematic overview of the study design is presented in Figure 1.

Health Screening Protocols During the Period After Calving. The daily health monitoring was carried out from DIM 1 after the morning milking by 3 veterinarians, 2 of whom were always present. All health alerts from the ear tag were displayed in the sensor system software and reviewed once a day in the morning by the documenting veterinarian before the start of the fresh cow health screening protocols. This person only shared the information on health alerts from the SEN group (not from the CON group) with the investigating veterinarian, who was the person examining the cows. Consequently, health alerts for CON cows were not available during the health monitoring period, but were used retrospectively for the statistical analysis. Different SOP-based health screening protocols were applied depending on the assignment of the cow (CON vs. SEN). The SOP included the definition of diseases the examination steps and treatments and are provided in Supplemental Table S1 (see Notes). The SOP were developed by the 3 veterinarians in collaboration with the herd health managers of the dairy farm.

The daily health screening and treatments for CON included fewer intensive investigation steps for all cows in comparison to SEN: a hypocalcemia prophylaxis with 120 mL calcium s.c. (CalciLift forte, Dechra Veterinary Products, Aulendorf, Germany), on DIM 0; assessment of milk yield deviations (≥25% daily milk yield deviations compared with the previous day, on ≥DIM 4); measurement of the rectal temperature; examination for occurrence of cold ears and body surface; and assessment of feeding behavior (i.e., visual observation of hay intake while animals were fixed in headlocks for fresh cow monitoring procedures). Additional examinations were performed for deviations from the physiological status of the monitored criteria and included estimation of rumen fill (**RF**), adapted from Zaaijer and Noordhuizen (2003); estimation of manure consistency (**MC**), adapted from Zaaijer and Noordhuizen (2003); and percussion auscultation if a displaced abomasum (**DA**) was suspected (RF ≤2; MC ≤2). A vaginal examination with a gloved hand was performed in case of retained placenta, and a vaginal examination and additional udder examination was performed in case of fever (rectal temperature ≥39.5°C). Hypocalcemia was defined as cold ears and cold body surface with or without ataxia, and ketosis was defined with decreased appetite and solid feces (MC >3).

To investigate the impact of a more intensive health screening strategy combined with a targeted health observation on the number of diagnosed disorders, cows in the SEN group were only examined after the onset of a sensor-based health alert. The algorithms that generated the health alerts are the intellectual property of the company. All SEN cows with health alerts were examined for at least 2 more days. In case of an ongoing health alert ≥3 d, the examination time was extended considering the rumination pattern of the individual animal. The health screening protocol for SEN cows with a health alert included: measuring rectal temperature; RF estimation; rumen auscultation and percussion auscultation; estimation of MC; rectal and udder examination; and determination of eye dehydration status as described by Constable et al. (2017). A vaginal examination was performed in case of fever. Independent of sensor-based health alerts, the calcium concentration in blood of SEN cows was regularly determined at DIM 0 and DIM 3 using an on-farm device (VETSCAN VS2 Chemistry Analyzer, Zoetis, Parsippany, NJ) with a blood calcium level <1.97 mmol/L as the threshold. In addition, the blood concentration of BHB was estimated for SEN cows at DIM 3 and 10 using a hand-held device (Freestyle Precision β-ketones, Abbott Diabetes Care Ltd., Oxon, United Kingdom) with a threshold of ≥1.2 mmol/L, regardless of the occurrence of health alerts. Cases of ketosis were classified as mild (BHB ≥1.2 mmol/L and <1.8 mmol/L), moderate (BHB ≥1.8 mmol/L and <3.0 mmol/L), or severe (BHB ≥3.0 mmol/L).

Definition of Disorders in Relation to Management Strategy. As the health examinations for cows of the SEN group were intensified, the definition of some disorders included the outcome of additional examination steps for SEN cows. Rumen dysfunction was diagnosed in CON cows with RF <3 and in SEN cows with the additional criteria of less than 2 rumen contractions in 3 min and a low intensity tone. A DA was defined as an abnormal movement of the fourth gastric compartment to the left or right abdomen, diagnosed by auscultation of the typical "ping" sound with finger to abdomen percussion. Mastitis was diagnosed as a swollen or painful udder with abnormal milk pattern (e.g., water or clots) and signs of illness such as depressed behavior, fever, or anorexia. Metritis was defined as a watery, purulent, or fetid uterine discharge with or without fever. A retained placenta was characterized as the remaining of fetal membranes within 24 h of calving. Lameness was defined as abnormal gait or stance according to Sprecher et al. (1997) and included interdigital phlegmon, which was defined as diffuse indistinct swelling in the interdigital region associated with lameness. In general, a period of 7 d was set for the same disorder to be re-diagnosed. All results of the daily fresh cow health monitoring protocols were documented in a spreadsheet and transferred to an Excel file (Microsoft Excel, version 2012). At the beginning of the study, a joint scoring of cows based on the examination steps was performed in order to ensure consistent observations by the 3 different examining veterinarians. In addition, weekly comparisons were made between the 2 veterinarians present on site at the time.

Definition of Sensor-Based Health Alerts and Initial Diagnoses. All cows were equipped with Smartbow (**SB**) ear tags (Smartbow ear tag, Smartbow/Zoetis, Weibern, Austria; size and weight 52 × 36 × 17 mm and 34 g) at least 4 mo before the study began. These ear tags recorded 3-dimensional acceleration data of head and ear movements at a frequency of 1 Hz, which was transmitted in real time to receivers and processed and analyzed using machine learning methods on a farm server. Company-specific algorithms provided a health alert triggered by a sharp decrease in rumination over the previous 24 h or based on a decrease in rumination time over several days. The operating principles of these algorithms are proprietary to the company. In our study, health alerts were defined as follows: A health alert occurring during the day was considered valid for the entire day, regardless of its duration. If the interval between 2 consecutive health alerts was less than 48 h, these alerts were considered as 1 connected event.

Animals without a clinical disorder diagnosis up to DIM 10 (CON) or up to DIM 16 (SEN) were classified as not affected (**na**), whereas cows with at least one initial diagnosis during this period were classified as diseased (**dis**). The initial diagnosis (**inD**) was defined as follows: The first lactation day of an abnormal condition based on the SOP health screening protocols of the defined diseases. A minimum of 7 d without treatment was required to re-diagnose the same condition. A health alert was considered as associated with the inD if it occurred in the range of 5 d before the day of inD until 2 d after inD.

In the retrospective analysis of the rumination time regarding the status of health alerts, all cows of the study were divided into 3 subgroups based on the status of the health alert and health condition. These subgroups included the rumination time of: (1) health alert and disease diagnosis (**alrt_dis**); (2) health alert and no diagnosis (**alrt_na**); and (3) no health alert (**nalrt**).

Statistical Analyses

The data were imported into the SPSS statistical software package (SPSS version 27.0.0.0, IBM Corporation) for analysis. The sample size was determined on performance data because reliable data on incidences of diseases at farm level were not available. Based on the previous herd data, 144 cows of each group were needed to detect a difference in milk yield of 500 kg per lactation with $\alpha = 0.05$, $\beta = 0.2$, and Power = 0.8 (G*Power Version 3.1.9.6, Heinrich Heine University Düsseldorf, Düsseldorf, Germany).

The normal distribution of the data was tested using the Shapiro-Wilk test and visual inspection. Differences in binary and qualitative outcomes between CON and SEN groups were analyzed using the Pearson chi-squared test or Fisher's exact test if the number of variables per group was less than 5. The Student's *t*-test was used to compare metric variables between CON and SEN groups. A *P*-value of ≤0.05 for differences between the groups was considered as significant.

The sensitivity (**SE**) of health alerts for the CON group was calculated as the proportion of cows diagnosed with disease that also had a health alert. The specificity (**SP**) of health alerts for cows of the CON group was calculated as the proportion of unaffected cows that did not have a health alert. For the calculation of SE and SP, the diagnoses of the investigating veterinarian were used as the reference standard.

The sensitivity of health alerts regarding hypocalcemia or ketosis of the SEN group was calculated as the proportion of cows diagnosed with disease by laboratory tests that also had a health alert. The specificity of health alerts regarding hypocalcemia or ketosis of the SEN group was calculated as the proportion of unaffected cows that did not have a health alert.

To calculate the rumination time of each cow per day, the accelerometer data per hour were aggregated and validated for data points available from the SB system for the respective animals and days. A cow's record was considered valid if it contained at least 18 h of accelerometer data per day during the period from 2 d before calving up to 16 d after calving. To detect differences in the average daily rumination time relative to calving between the alrt_dis, alrt_na, and nalrt subgroups, a mixed ANOVA of repeated measurements was conducted. The lactation day was considered as a dependent intrasubject factor and the subgroups (alrt_dis, alrt_na, nalrt) as the independent intersubject factor. The LSD post hoc mean separation test was used to determine differences between subgroups. All averages are reported as mean ± SEM with a 95% confidence interval if no different indication was given.

RESULTS

Descriptive Data of Study Animals

Of the study cows, 400 (CON n = 199, SEN n = 201) had a record of at least 18 h of accelerometer data per day in the period of 2 d a.p. up to 16 d postpartum due to deviations in investigations and treatments of the SOP during the monitoring period, 5 cows of the SEN group were further excluded. Consequently, the final data set contained 396 cows (CON n = 199; SEN n = 197). No differences in the number of lactations (CON 3.41 ± 0.09, SEN 3.34 ± 0.09; *P* = 0.28) or milk yield in the previous lactation (305 d, CON 11,863 ± 117 kg, SEN 11,704 ± 118 kg; *P* = 0.34) were found between both health monitoring groups. Furthermore, CON and SEN cows did not differ in BCS during the study period, at d 60 ± 3 a.p. (3.00 vs. 2.94; *P* = 0.12), d 21 ± 3 a.p. (3.12 vs. 3.08; *P* = 0.25), d 7 ± 3 a.p. (3.16 vs. 3.10; *P* = 0.06), or at the day of calving (3.10 vs. 3.06; *P* = 0.26). During the period after calving, CON cows were continuously monitored for 10 ± 0 d, and SEN cows were monitored for 3.8 ± 1.6 d (*P* < 0.01) out of 16 possible days at risk because of a health alert.

During the days at risk, 236 cows (79%) had at least 1 health alert (115 health alerts for 111 CON cows; 131

Table 1. Descriptive statistics (mean ± SEM) for the distribution of health alerts among the management groups CON (conventional health monitoring protocol already initiated on the farm) and SEN (intensive health monitoring protocol based on the occurrence of health alerts)

Parameter	Management group		P-value
	CON (n = 199)	SEN (n = 197)	
Health alerts (n)	115	131	
Cows with a health alert (n)	111	125	0.12
Health alerts per cow (n)	1.04 ± 0.02	1.05 ± 0.02	0.65
1 health alert (n)	107	119	0.65
2 health alerts (n)	4	6	0.65
Start of health alert (DIM[1])	−0.22 ± 0.22	0.18 ± 0.20	0.16
Duration of health alert (d)	3.31 ± 0.22	3.46 ± 0.24	0.33

[1]Relative to parturition (DIM 0 = day of parturition).

health alerts for 125 SEN cows). Those health alerts started on average at DIM −0.22 ± 0.22 for CON cows and at DIM 0.40 ± 0.20 for SEN cows (Table 1). The duration of captured health alerts did not differ between groups (CON 3.31 ± 0.22 d, SEN 3.46 ± 0.24 d; P = 0.33). Most health alerts (n = 218, 87%) were present on DIM 1 (CON n = 104; SEN n = 114).

Inter-Rater and Intrarater Agreement of Examination Steps

To ensure the reliability of the assessment steps between the 3 different investigating veterinarians, all assessment schemes were evaluated at the beginning of the study, and selected parameters were re-evaluated at weekly intervals during the study period. For the assessment of the intrarater agreement, each veterinarian re-scored the evaluation schemes, that were repeatable (i.e., lameness and body condition score) the next day.

Table 2. Inter-rater agreement between 3 different investigating veterinarians for the assessment schemes used in the study; Cohen's kappa (κ) and intraclass correlation coefficient (r_{ICC})

Evaluation scheme	Events (n)	κ[1]	r_{ICC}[1]
Measurement of rectal temperature	98		0.96
Estimation of rumen fill[2]	100	0.97	
Rumen simultaneous auscultation	103	0.98	
Succession and percussion auscultation	103	0.98	
Manure consistency[3]	101	0.89	
Rectal examination	103	0.47	
Udder examination	103	0.99	
Dehydration score[4]	103	0.99	
Vaginal examination	15	0.99	
Lameness score[5]	103	0.98	
Body condition score[6]	103		0.95

[1]$P < 0.001$ for Cohen's kappa and intraclass correlation coefficients.
[2]Estimation of rumen fill, adapted from Zaaijer and Noordhuizen (2003).
[3]Manure consistency, adapted from Zaaijer and Noordhuizen (2003).
[4]Dehydration score, as described by Constable et al. (2017).
[5]Lameness score, according to Sprecher et al. (1997).
[6]Body condition score, according to Edmonson et al. (1989).

The inter-rater agreement (Cohen's κ) ranged from 0.47 to 0.99, and the intraclass correlation coefficient (**r_{ICC}**) was ≥ 0.95 (Tables 2 and 3). For the intrarater agreement, an r_{ICC} ≥ 0.86 was found (Table 3).

Health Alerts and Initial Diagnoses

At least 1 inD was observed for 99 cows during the days at risk (70 inD for 49 CON cows; 78 inD for 50 SEN cows). No differences were found between CON and SEN in the relative number of animals with inD (24.6% vs. 25.4%; P = 0.73), nor in the average number of inD per cow (1.4 ± 0.1 vs. 1.6 ± 0.1; P = 0.5). The earliest inD was observed for CON cows at DIM 3.1 ± 0.3 and for SEN cows at DIM 2.8 ± 0.4, (P = 0.57), respectively (Table 4). Figure 2 presents the number of CON and SEN cows with diagnoses and health alerts in the period around calving.

The most frequent initial diagnoses in the CON group were fever of unknown etiology (n = 17) and retained placenta (n = 12). For SEN cows, rumen dysfunction (n = 29) and lameness (n = 16) were diagnosed most frequently (Table 5). Furthermore, cows in the CON group had a greater incidence of diagnosed fever of unknown origin than cows in the SEN group (P = 0.02), whereas cows of the SEN group showed a greater incidence of rumen dysfunction than cows in the CON group (P < 0.01). No differences were observed between the groups for other disorders.

In general, more SEN cows with health alerts had at least one inD than cows in the CON group with health alerts (CON n = 33, SEN n = 50; P = 0.04; Table 6). The most inD of both groups were recorded during an ongoing health alert, rather than before or after a health alert. Furthermore, the mean interval between the start of a health alert and the earliest inD was shorter for SEN cows than for CON cows (CON: 4.2 ± 0.7 d, SEN: 2.5 ± 0.3 d; P = 0.01). In addition, CON cows showed a sensitivity of 71% and a specificity of 47% for health alerts.

Table 3. Intrarater agreement between 3 different investigating veterinarians (Vet1–3) for the comparable assessment schemes used in the study, intraclass correlation coefficient (r_{ICC})

Evaluation scheme	Events (n)	r_{ICC}[1] Vet1	Vet2	Vet3
Body condition score[2]	24	0.96	0.96	0.97
Lameness score[3]	24	0.86	0.86	0.86

[1]$P < 0.001$ for intraclass correlation coefficients.

[2]Body condition score, according to Edmonson et al. (1989).

[3]Lameness score, according to Sprecher et al. (1997).

Table 4. Descriptive statistics (mean ± SEM) for the distribution of inD among the management groups CON (conventional health monitoring protocol already initiated on the farm) and SEN (intensive health monitoring protocol based on the occurrence of health alerts)

Parameter	Management group CON (n = 199)	SEN (n = 197)	*P*-value
Number of inD	70	78	
Number of cows with inD	49	50	0.69
Number of inD per cow	1.4 ± 0.1	1.6 ± 0.1	0.50
1 diagnosis	35	33	0.32
2 diagnoses	7	9	0.32
3 diagnoses	7	5	0.32
4 diagnoses	0	3	0.32
DIM of earliest inD	3.1 ± 0.3	2.8 ± 0.4	0.57

[1]Relative to parturition (DIM 0 = day of parturition).

Routine Monitoring of SEN Cows for Ketosis and Hypocalcemia

Ketosis was regularly diagnosed for 68 SEN cows (n = 10 at DIM 3; n = 58 at DIM 10) with an incidence of 35%. Based on the blood levels of BHB, the cases of ketosis for SEN cows were divided into mild (n = 58, 85%), moderate (n = 9, 13%), and severe (n = 1, 2%). A health alert during the fresh cow period was present for 50 SEN cows (70%) that suffered from ketosis, resulting in a SE of 71% and a SP of 48%. At least 1 other diagnosis was recorded for 24 (34%) of the animals that suffered from ketosis.

The diagnosis of hypocalcemia was regularly observed for 76 SEN cows by the on-farm device, mostly at DIM 0 (inD: n = 74 at DIM 0; n = 2 at DIM 3) with an incidence of 39%. A rumination alert was present for 126 SEN cows (64%), resulting in a SE of 75% and a SP of 43%. At least 1 other diagnosis was recorded for 32 (42%) of the animals that suffered from hypocalcemia.

Rumination Times

All studied cows from CON and SEN were retrospectively classified based on their rumination times during the period around calving into 3 groups: health alert connected to disorders (alrt_dis; n = 126), health alert with no connected disorder (alrt_na; n = 117), and no health alert (nalrt; n = 153). Both groups with health alerts (alrt_dis and alrt_na) differed consistently between rumination time from DIM 1 until DIM 3 ($P \le 0.01$). Focusing on the rumination time of cows with current health alerts per lactation day (Figure 3) for this period, it was observed that 24% to 36% of alrt_dis cows had rumination times below the range covered by 98% of the nalrt group from DIM 1 until DIM 3 (DIM 1 = 31%; DIM 2 = 36%; DIM 3 = 24%). In contrast, 7% to 10% of alrt_na cows with a current health alert had rumination times per day below the range covered by 98% of the nalrt group from DIM 1 until DIM 3 (DIM 1 = 9%; DIM 2 = 10%; DIM 3 = 7%).

The rumination time of alrt_dis cows consistently differed from that of nalrt cows from DIM −6 until DIM 3 ($P \le 0.01$). In contrast, the rumination time between nalrt and alrt_na cows only consistently differed from DIM −2 until DIM 1 ($P \le 0.01$). Consequently, the rumination time was influenced by the lactation days ($P < 0.001$), as well as the interaction between lactation days and subgroups ($P < 0.001$), as shown in Table 7. No difference was found for the single factor of subgroups ($P = 0.17$).

DISCUSSION

The aim of the study was to determine the effectiveness of health alerts. First, the accuracy of health alerts was analyzed in the context of 2 health monitoring strategies (CON and SEN), which were compared with each other. Second, the course of rumination was investigated for all study cows as a function of health alert status and health condition. The focus was on disorders occurring within a maximum of 16 d after calving.

Parameters such as the number of lactations and milk yield influence the rumination time of dairy cows (Maekawa et al., 2002; Cocco et al., 2021). We compared milk yield, lactation numbers, and BCS in both the CON and SEN groups to establish a study baseline. Finding no differences, we considered both groups to have similar health status entering the postpartum period. This similarity allowed us to attribute health changes to postpartum metabolic conditions and management strategies.

Analyzing the specific initial diagnoses, CON cows experienced a greater number of fevers of unknown etiology, whereas SEN cows experienced a greater number of rumen dysfunctions. This can be attributed to the fact that the CON health screening protocol primarily focused on daily temperature measurement, whereas SEN cows were only subjected to temperature measurements in the case of the occurrence of a health alert. Conversely, rumen function was more closely monitored through rumen auscultation for cows in the SEN group than for CON cows. Based on the differences between the 2 groups concerning

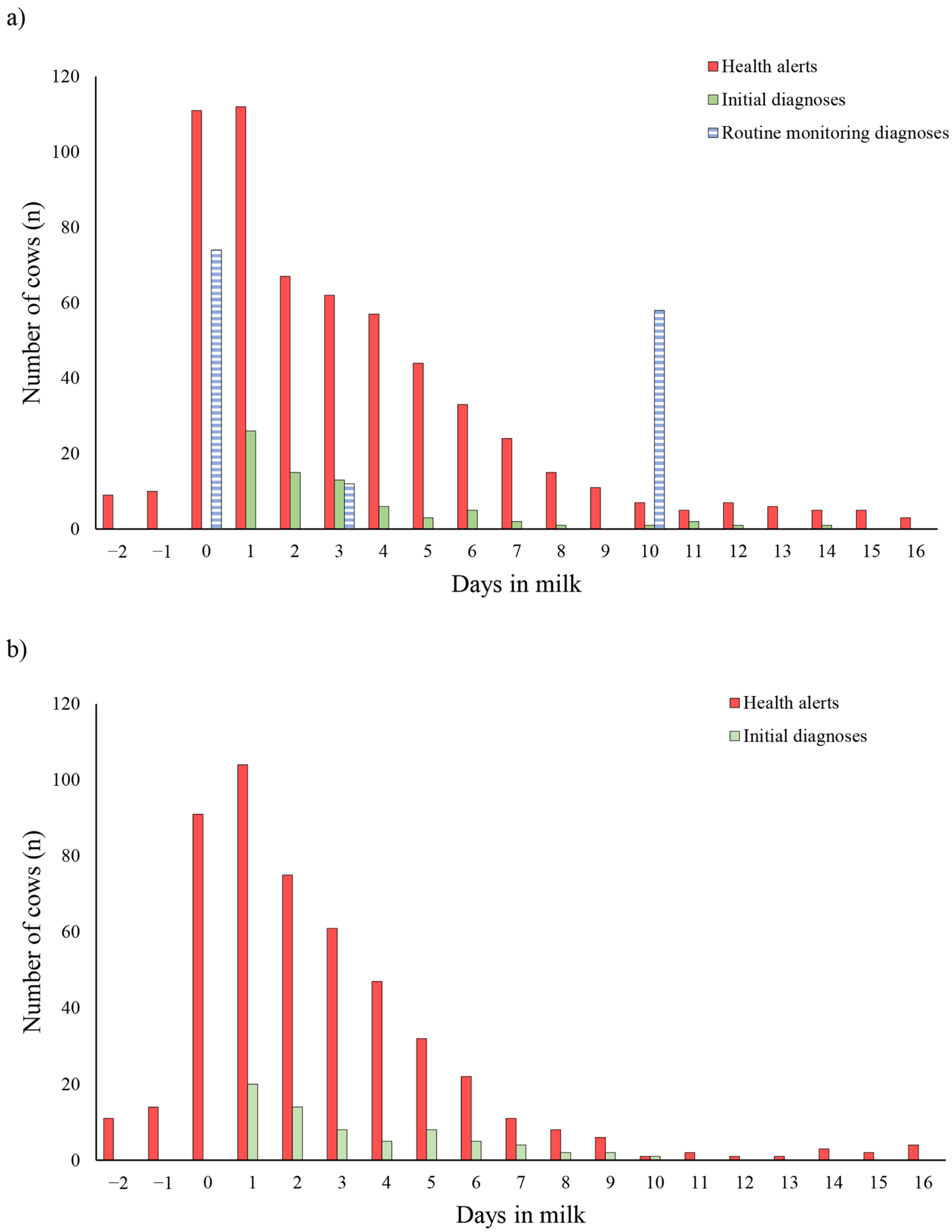

Figure 2. (a) Distribution of health alerts, initial diagnoses, and initial diagnoses of routine monitoring (blood levels of calcium at DIM 0 and 3; blood levels of BHB at DIM 3 and 10) of the SEN group per cow and per day during the peripartum period. (b) Distribution of health alerts and initial diagnoses of the CON group per cow and per day during the peripartum period.

these 2 specific diagnoses, it seems that cases of rumen dysfunction may have been diagnosed in greater numbers in the SEN group due the additional examination step of rumen auscultation. On the contrary, cases solely of fever of unknown etiology might not cause a health alert. The findings of Stangaferro et al. (2016a) support the assumption that rumination times are more affected by metabolic disorders, whereas the presence of fever did not affect rumination times in the case of metritis (Stangaferro et al., 2016c). A decrease in rumination time might be more closely linked to the digestive system (Simoni et al., 2023) than to inflammatory processes related to fever. In

Table 5. Incidence of disorders based on the applied health monitoring protocols during the days at risk for cows of the CON (conventional health monitoring protocol already initiated on the farm) and SEN group (intensive health monitoring protocol based on the occurrence of health alerts), as well as the day of diagnosis (DIM relative to parturition) for those disorders (mean ± SEM)

	Management group				
Parameter	CON (n = 199)	n	SEN (n = 197)	n	*P*-value
Incidence, %					
Fever of unknown etiology	9[a]	17	3[b]	6	0.02
Rumen dysfunction	2[a]	4	15[b]	29	<0.01
Mastitis	1	1	1	1	0.99
Metritis	6	11	5	10	0.84
Retained placenta	6	12	6	11	0.85
Lameness	4	8	8	16	0.09
Disturbed general condition	0	0	2	3	
DIM at diagnosis	3.1 ± 0.4	48	2.8 ± 0.4	51	0.57
Fever of unknown origin	3.8 ± 0.6	17	4.8 ± 1.6	6	0.54
Rumen dysfunction	2.8 ± 0.8	4	2.6 ± 0.6	29	0.89
Mastitis	7.0 ± 0.0	1	3.0 ± 0.0	1	
Metritis	5.0 ± 0.8	11	3.7 ± 0.5	10	0.09
Retained placenta	1.3 ± 0.2	12	1.1 ± 0.1	11	0.44
Lameness	5.6 ± 0.6	8	4.8 ± 0.8	16	0.21
Disturbed general condition	0	0	4.3 ± 0.9	3	

[a,b]Incidences within rows with different superscripts differ.

conclusion, these differences can be explained by both the different focus of health strategies and the different impairment of rumination time for different disorders. In our study, the average lactation day a diagnosis was made aligned with Gusterer et al. (2020), who also used variables of SB for the early detection of health disorders in dairy cows. These findings indicated a brief interval between calving and the initial diagnosis of disorders. The average day of diagnosis occurred earlier compared with the studies by Silva et al. (2021) and Stangaferro et al. (2016a). All mentioned studies monitored dairy cows for common disorders during the peripartum period, but the description of the specific monitoring procedures, days of monitoring, and intensity of monitoring varied across the different studies. Furthermore, in our study, as well as in the study conducted by Gusterer et al. (2020), the examination and treatment procedures were carried out in accordance with SOP and only performed by veterinarians, rather than farm personnel. In addition, the same sensor system was used. This may have led to an earlier detection of deviant health conditions, which is beneficial for the evaluation of the accuracy of health alerts but might also not be practically feasible on commercial dairy farms.

Implementing health alerts on the farm does not yet enable distinction between different diagnoses of disorders (Stangaferro et al., 2016c). Consequently, we decided not to analyze the retrospective SE and SP of health alerts for specific disorders, except for SEN routine ketosis and hypocalcemia monitoring, which was done independently from the occurrence of health alerts.

Ketosis and hypocalcemia during the peripartum period are regularly associated with a reduction in rumination time (Goff et al., 2020; Tsai et al., 2021; Antanaitis et al., 2023). In our study, the SE of health alerts for ketosis was 71%, and the SP was 48%. These values were lower compared with Stangaferro et al. (2016a), who reported an SE of 91% for ketosis diagnosed on a

Table 6. Evaluation (mean ± SEM) of rumination alert and the earliest inD for CON (conventional health monitoring protocol which was already initiated on the farm) and SEN cows (intensive health screening protocol based on the occurrence of health alerts)

	Health screening protocol		
Parameter	CON (n = 199)	SEN (n = 197)	*P*-value
Earliest inD associated with health alert (n)	33[a]	50[b]	0.03
Earliest inD before start of health alert	3	1	0.32
Earliest inD during health alert	20[a]	33[b]	0.05
Earliest inD after health alert	10	16	0.21
Interval between health alert to earliest inD (d)	4.2 ± 0.7[a]	2.5 ± 0.3[b]	0.01

[a,b]Values within rows with different superscripts differ.

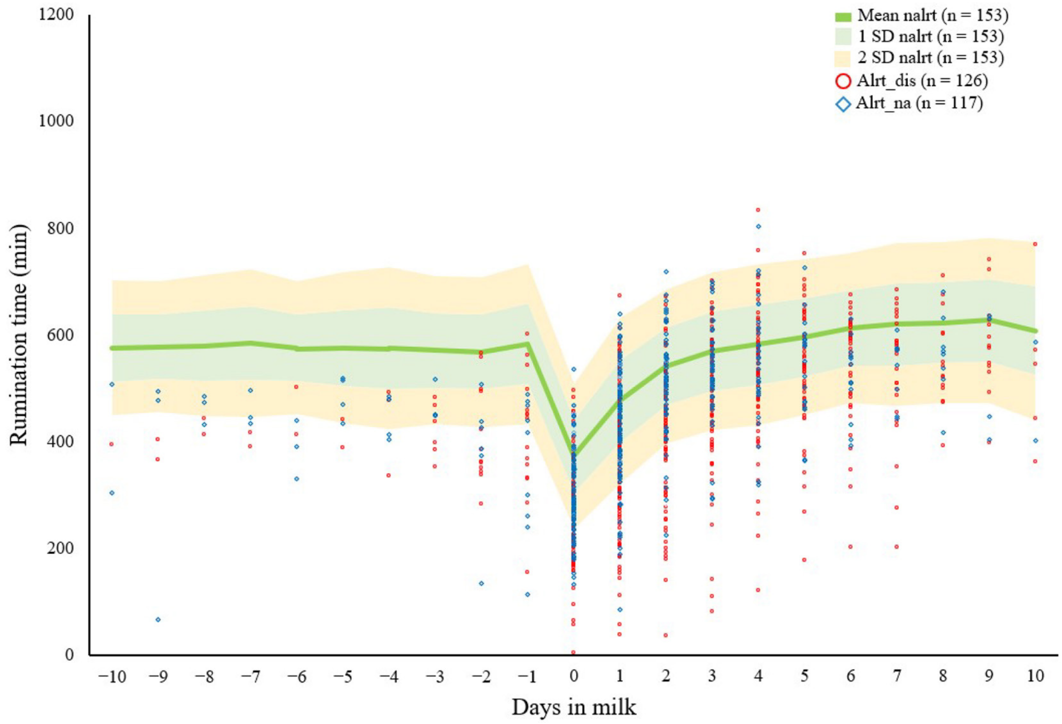

Figure 3. Mean rumination time per day (green line), as well as the rumination time of 68% (1 SD; green area) and 98% (2 SD; yellow area) of cows without a health alert (nalrt; n = 153) during the period around calving. The blue diamonds represent rumination times of a current health alert for all cows with no associated diagnosis (alrt_na; n = 117), whereas the red circles represent rumination times for a current health alert of all cows with associated diagnoses (alrt_dis; n = 126).

Table 7. Differences in rumination times (min) between cows with a health alert and initial diagnosis (alrt_dis), cows with a health alert and no initial diagnosis (alrt_na), and cows with no health alerts (nalrt) from DIM −10 until DIM 10

	Rumination time[1]			*P*-value		
DIM[2]	alrt_dis (n = 126)	alrt_na (n = 117)	nalrt (n = 153)	alrt_dis vs. alrt_na	alrt_dis vs. nalrt	nalrt vs. alrt_na
−10	569 ± 82	564 ± 86	575 ± 63	1.00	1.00	0.67
−9	563 ± 78	566 ± 103	577 ± 61	1.00	0.42	0.82
−8	558 ± 84	562 ± 104	579 ± 66	1.00	0.12	0.28
−7	559 ± 87	563 ± 96	584 ± 69	1.00	0.04	0.12
−6	544 ± 81	562 ± 92	575 ± 62	0.22	<0.01	0.51
−5	542 ± 88	556 ± 90	575 ± 71	0.52	<0.01	0.16
−4	541 ± 95	544 ± 84	575 ± 76	1.00	<0.01	0.01
−3	536 ± 93	547 ± 93	570 ± 69	0.95	<0.01	0.07
−2	534 ± 99	540 ± 111	568 ± 70	1.00	0.01	0.05
−1	525 ± 114	539 ± 115	583 ± 75	0.90	<0.01	<0.01
0	291 ± 98	309 ± 78	373 ± 68	0.23	<0.01	<0.01
1	387 ± 127	437 ± 104	477 ± 78	<0.01	<0.01	0.01
2	459 ± 132	529 ± 90	541 ± 72	<0.01	<0.01	1.00
3	517 ± 122	559 ± 88	569 ± 74	0.01	<0.01	1.00
4	561 ± 115	574 ± 93	581 ± 75	0.78	0.20	1.00
5	579 ± 109	594 ± 88	595 ± 73	0.52	0.39	1.00
6	603 ± 109	608 ± 81	613 ± 70	1.00	1.00	1.00
7	611 ± 103	614 ± 78	619 ± 77	1.00	1.00	1.00
8	624 ± 88	615 ± 89	623 ± 76	1.00	1.00	1.00
9	627 ± 88	602 ± 111	627 ± 77	0.10	1.00	0.09
10	620 ± 90	595 ± 105	607 ± 83	0.09	0.73	0.80

[1]Rumination times are presented as means ± SD.

[2]Relative to parturition (DIM 0 = day of parturition).

similar average DIM compared with our study (DIM 9.3 vs. DIM 9.0). They conducted a daily testing routine for urine ketone bodies, whereas our routine monitoring was on DIM 3 and 10, which may have limited the detection of true positive cases (Cocco et al., 2021). Paudyal et al. (2018) monitored cows routinely on DIM 4, 7, and 12 for health disorders such as ketosis and reported an SE of 61%, closer to our study, and a SP of 84%.

The routine monitoring of hypocalcemia in our study resulted in an SE of 77% and a SP of 48% for cows predominantly affected by subclinical hypocalcemia. In the study by Paudyal et al. (2018), an SE of 100% and an SP of 85% were reported, but their study design considered clinical hypocalcemia solely defined by down or unsteady cows around calving with no other deviation in health condition.

The accuracy of initial diagnoses of the CON cows showed an SE of 71% and an SP of 47%. Previous studies have reported SE for different disorders ranging from 42 to 100% and SP of 84% to 85% (Stangaferro et al., 2016a,b; Paudyal et al., 2018). Stangaferro et al. (2016c) also reported an overall SE of 59% and SP of 98% for detecting metabolic and digestive disorders, mastitis, and metritis. What is particularly striking about these studies is the great SE of the health alerts compared with our study. Both studies used longer observation periods (60–80 lactation days vs. 16 lactation days) and calculated SE and SP on a daily level. Each day outside the range associated with health alerts and diagnosis was defined as a true negative day. Because the transition period is characterized by a series of metabolic changes, a longer observation period led to an additional lower incidence of disorders. Indicating proportionally more days without health alerts and diagnoses than the occurrence of diagnoses at all, this approach leads to a large number of true negative events (Stangaferro et al., 2016c; Paudyal et al., 2018). The results of our study highlight a disparity between the great number of cows experiencing health alerts compared with cows with initial diagnoses. Applying an approach that led to many true negative events would obscure this result. Furthermore, farmers may prioritize identifying whether cows with health alerts exhibit any disorders rather than being informed about SE and SP for each day within a specific range of days of diagnoses that are associated with health alerts. Consequently, we conducted a cow-based approach to assess SE and SP. Each cow included in the study had a single outcome in terms of health alerts and initial diagnoses during the study period. When considering the previous studies as a reference for our CON group, applying their approaches would have led to SE ranging from 67% to 78% and SP ranging from 85% to 86%.

To evaluate the SE and SP achieved in our study, the added value of the health alerts based on a farm's initial monitoring situation should be considered. A farm with a low disease detection rate would benefit more from a higher sensitivity, as each detected case accounts for a large proportion. In contrast, a farm with a high detection rate would benefit from the same sensitivity as it would find almost every disorder before clinical diagnosis. This poses challenges for making general statements. In addition, a high rate of false positive health alerts, which was found in our study, could raise doubts regarding the validity of health alerts by farmers (Eckelkamp and Bewley, 2020; Tsai et al., 2021). Moreover, implementing the SEN monitoring on farm without the routine monitoring for ketosis and hypocalcemia did not significantly increase the total number of initial diagnoses within the first 16 d of lactation, suggesting the CON monitoring strategy was adequate for this farm. Nevertheless, this view does not take into account the potential benefits of health alerts throughout the lactation period or the economic aspects of introducing health alerts on commercial dairy farms.

A detailed examination of the general course of rumination times within the 3 subgroups (alrt_dis, alrt_na, and nalrt) revealed notable variations occurring around the time of calving. Several studies (Büchel and Sundrum, 2014; Clark et al., 2015; Giaretta et al., 2021) have previously investigated changes in rumination time and activity during the calving period, attributing these changes to the physiological process of calving itself. In our study, the nalrt group served as a benchmark for physiological changes occurring around calving, as this subgroup did not exhibit any health alerts during our study period. The alrt_dis subgroup displayed continuous differences in rumination behavior compared with the nalrt subgroup, starting 6 d before calving and persisting until 3 d after calving. This finding aligns with previous research by Soriani et al. (2012), indicating that cows with peripartum disorders exhibit changes in rumination behavior during the close-up period. Although the nalrt cows experienced a sharp increase in rumination time after calving, we observed, similar to Soriani et al. (2012), that the alrt_dis subgroup took the longest time to recover from the initial decrease in rumination time during calving.

No overall differences were observed between the subgroups, which can be attributed to the 43-d period of rumination time considered for statistical analyses, as well as the aggregated changes in rumination time occurring specifically around calving. In retrospect, the course of rumination time may serve as one component of reliable indicators for detecting peripartum disorders in cows. From a practical standpoint, farmers require a prospective view to effectively respond to health alerts. The narrow interval between calving and d 0 poses challenges for the algorithms of the system to distinguish between a decrease in rumination time caused by calving itself versus a decrease caused by a disorder. This assumes that calving can be reliably predicted in the first place. Other studies assessing rumination time tended to exclude the days around calving from their analyses (Schirmann et al., 2016; Stangaferro et al., 2016c) or consider the days around calving as an extra period (Hut et al., 2022). Keeping in mind the short interval between calving and initial diagnosis, this period is important to consider for the implementation of health alerts.

CONCLUSIONS

Our study examined the accuracy of sensor-based health alerts and the effectiveness of 2 management strategies on a commercial dairy farm. Despite the greater SE and SP of the health alerts based on the SEN monitoring strategy compared with the CON strategy, discrepancies between the number of health alerts and initial diagnoses were observed for both groups during the peripartum period. The effectiveness of health alerts may depend on the initial situation of herd health management on individual farms. The rumination curve during the peripartum period could be a potential indicator for cows with disorders. Further research is needed to evaluate health alerts in different practical settings, considering economic factors as well. Additionally, establishing a baseline for rumination time around calving would improve the integration of this physiological process into future algorithms for disease detection.

NOTES

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Nonstandard abbreviations used: a.p. = antepartum; alrt_dis = health alert and disease diagnosis; alrt_na = health alert and no diagnosis; CON = conventional management group; DA = displaced abomasum; dis = diseased; GHO = general health observation; inD = initial diagnosis; L = lameness score; MC = manure consistency; na = not affected; nalrt = no health alert; RF = rumen fill; r_{ICC} = intraclass correlation coefficient; SB = Smartbow; SE = sensitivity; SEN = sensor-based management group; SOP = standard operating procedure; SP = specificity; Vet1–3 = investigating veterinarians 1–3; κ = Cohen's kappa.

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