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Effect of automated health monitoring based on rumination, activity, and milk yield alerts versus visual observation on herd health monitoring and performance outcomes

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ABSTRACT

A primary objective of this randomized trial was to compare the percentage of cows that underwent clinical examination and were diagnosed with clinical health disorders (CHD) using a health monitoring program that relied only on automated monitoring system alerts versus a program that relied only on visual observation of clinical signs of disease to select cows for clinical examination. Another objective was to compare the effects of these health monitoring programs on milk yield, the herd exit dynamics (i.e., cows sold and dead), and first service reproductive outcomes. Lactating Holstein cows (n = 1,204) enrolled in the experiment were fitted with a neck-attached sensor of an automated monitoring system (HR Tags; Merck & Co. Inc.) that generated health alerts based on rumination time and activity. Milk yield was monitored 3 times per day by automated milk meters (MM27BC, DeLaval). Cows were blocked by parity, close-up period diet, and stratified by previous lactation milk yield, and then were randomly assigned within block to different programs for monitoring health from 3 to 21 DIM. Cows in the visual observation group (VO; n = 597) were selected for clinical examination exclusively based on visual observation of clinical signs of disease, whereas cows in the automated health monitoring group (AHM; n = 607) were selected for clinical examination based on health alerts consisting of the following: a health index score <86 arbitrary units, daily rumination <250 min, or a reduction of >20% in daily milk yield. Once selected for examination, the clinical exam was the same for both treatment groups. Binary data such as the occurrence of CHD, herd exit, and pregnancies per AI were analyzed with logistic regression. Daily and weekly milk yield were analyzed using ANOVA with repeated measurements. More cows underwent a clinical examination, more cows were diagnosed with at least one CHD, and more cows received treatment in the AHM group than the VO treatment group. Cows in the AHM treatment had more accumulated milk than cows in the VO treatment from 2 to 21 DIM. Cows in the AHM treatment diagnosed with at least 1 CHD produced more milk from 3 to 18 and 20 to 21 DIM than cows diagnosed with a CHD in the VO treatment. Fewer cows left the herd up to 21 DIM for the AHM than the VO treatment. Pregnancies per AI at first service were greater for the VO than the AHM treatment at 30 d but not at 50 d after AI, and no difference in pregnancy loss was detected. Overall, a health monitoring strategy that used automated health alerts increased the risk of undergoing clinical examination and having CHD diagnosed compared with a program that selected cows for clinical examination based exclusively on VO. Cows monitored with the program that relied on automated alerts also had greater milk yield in the first 21 DIM. Thus, monitoring cow health based on automated behavior and milk yield alerts might be a more effective alternative for health monitoring than exclusive use of visual observation of clinical signs of disease.

Key words: dairy cow, sensors, automation, visual observation

INTRODUCTION

Dairy cows that fail to adapt to the substantial metabolic and immunological changes experienced during the early postpartum period are at greater risk of displaying clinical health disorders (Carvalho et al., 2019; Pinedo et al., 2020b). Beyond immediate detrimental effects of disease on health, well-being, and productivity, cows that present at least 1 clinical health disorder event during early lactation have reduced milk yield, poorer reproductive performance, and are at greater risk of leaving the herd (Bareille et al., 2003; Hostens et al., 2012; Liang et al., 2017). To mitigate the negative consequences of poor health, dairy farms implement health monitoring programs to identify cows with health disorders (Espada-

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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.

mala et al., 2016; Kerwin et al., 2022). Providing timely and appropriate treatments or interventions helps cows recover from clinical signs, reduces the probability of experiencing concomitant disorders, return to a normal trajectory of milk production, and mitigates other negative effects on long-term production and performance (McArt et al., 2012; Carvalho et al., 2019; de Oliveira et al., 2020).

Traditionally, typical health monitoring programs implemented on dairy farms relied on the identification of clinical signs of disease displayed by cows (Espadamala et al., 2016; Kerwin et al., 2022; König et al., 2023). For example, Kerwin et al. (2022) reported that 80% of farms used visual observation (**VO**) to select cows for clinical examination. A caveat of this approach is that the success of the program depends greatly on the availability, skillset, and experience of the technicians in charge of identifying and selecting cows for further examination. Due to time constraints for farm personnel conducting multiple tasks in small and larger herds, more cows to monitor in larger herds, and scarcity of qualified personnel to conduct herd management tasks (Espadamala et al., 2016; Kerwin et al., 2022), dairy farms need alternative approaches to identify cows with clinical health disorders. In this regard, automated monitoring systems based on sensors that monitor cow behavioral, physiological, and performance parameters are an alternative for monitoring cow health. These automated monitoring systems continuously monitor parameters known to be associated with sickness behavior (Stangaferro et al., 2016a,b,c; Gusterer et al., 2020; Rial et al., 2023a,b), and in some cases can monitor physiological and performance changes observed in cows undergoing health disorders (Norberg et al., 2004; Stangaferro et al., 2016a,b,c; Antanaitis et al., 2023).

Among the potential benefits of automated monitoring systems, the possibility of identifying cows for clinical examination allows farm personnel to focus only on cows potentially affected by health disorders and avoid unnecessary examination of cows not affected by health disorders (Perez et al., 2023). However, unlike the growing body of evidence that sensor-monitored parameters are altered in cows that experience clinical health disorders (Liboreiro et al., 2015; Stangaferro et al., 2016a,b,c; Rial et al., 2023a,b), little is known about the effects of implementing health monitoring programs that rely primarily or exclusively on data from automated monitoring systems to select cows for clinical examination. Very few randomized controlled experiments compared the performance of automated health monitoring (**AHM**) systems to traditional health monitoring strategies. Some experiments provided evidence that health monitoring programs that include (Silva et al., 2021a) or rely primarily (Perez et al., 2023) on automated monitoring systems alerts and data could be as effective as health monitoring programs that include more intensive traditional strategies to identify cows with health disorders, such as mandatory clinical examinations of all cows. On the contrary, there is a major knowledge gap about the potential benefits of health monitoring programs that rely on automated monitoring systems alerts compared with less intensive strategies that rely exclusively or almost exclusively on VO. This is relevant because many farms continue to use VO to select cows for clinical examination (Espadamala et al., 2016; Kerwin et al., 2022; König et al., 2023). Because they continuously and objectively monitor of cow health, automated monitoring systems that record behavioral, physiological, and performance parameters in real-time may offer benefits when compared with strategies based on intermittent and subjective observations of cow health, such as VO of sickness behaviors. For example, it is plausible that more cows with health disorders could be identified, and cows identified might be detected earlier with automated monitoring systems than through VO only.

Therefore, we hypothesized that a health monitoring program that relied only on automated monitoring systems data to select cows for clinical examination would result in the detection of more cows with clinical health disorders than a health monitoring program that relied exclusively on VO of signs of sickness. Moreover, we hypothesized that a consequence of detecting more cows with health disorders would improvement of herd performance outcomes through prompt treatment. Specifically, we expected that the use of automated monitoring systems would result in greater milk production, fewer cows exiting the herd, and improved first service reproductive performance. Thus, a primary objective of this randomized controlled trial was to compare the proportion of cows selected for clinical examination and cows diagnosed and treated for clinical health disorders for a health monitoring program that relied only on automated monitoring systems alerts versus a program that relied only on VO of clinical signs of disease. Another objective was to compare the herd exit dynamics, first service reproductive outcomes, and milk yield up to mid-lactation for cows managed with these health monitoring and management programs.

MATERIALS AND METHODS

All procedures performed with cows were approved by the Animal Care and Use Committee of Cornell University (Ithaca, NY; protocol #2017-0024).

Cows and General Management

This study was conducted at a commercial dairy farm located in Windsor, Colorado, from April to October of 2023. The farm was selected for the study because the automated monitoring system required for data collection was already installed and functional, DairyComp305 (ValleyAg Software, Tulare, CA) was used for dairy herd management, and the farm management team agreed to allow the research team to conduct the experimental procedures.

During the experiment, the farm housed an average of 5,325 (range: 5,178–5,430) milking and 672 (range: 522–796) dry Holstein cows. Daily milk yield (**MY**) per cow for the whole herd during the study period was 41.6 kg/d (range: 38.9–52.1 kg/d) and accumulated MY to 305 d for cows that calved during the study period was 11,308 kg (range: 4,395–16,810 kg). Cow numbers and MY data were retrieved from the dairy herd management software using the ECON\ID command.

Between 18 and 26 d before the expected parturition date, parous and nulliparous cows were moved to a close-up pen. Nulliparous and parous cows were housed in 2 different pens in the same 3-row freestall barn with deep sand-bedded stalls and fans and sprinklers for heat abatement. Every 1 h, farm personnel monitored cows visually during a walkthrough of each pen to identify cows with overt signs of calving (i.e., observation of allantoic sac or calf, restlessness) which were then moved to a maternity pen bedded with straw. Calving was monitored and assistance was provided when needed as determined by the attending calving manager.

After calving, all multiparous cows received Ca and vitamin D_3 supplementation through a ruminal bolus (Bovikalc, Boehringer Ingelheim Animal Health USA Inc., Duluth, GA) within 2 h of parturition. Within ~3 to 12 h after parturition, cows were moved to lactating cow 2-row barns where primiparous and multiparous cows were commingled in a single cow pen until 15 to 21 DIM (herein referred to as the fresh pen). After leaving the fresh pen, primiparous and multiparous cows were moved to high-producing pens based on parity (primiparous vs. multiparous).

Cows were milked 3 times per day at ~8 h intervals in a 90-stall rotary parlor equipped with individual stall milk meters (MM27BC, DeLaval) for capturing milk weights at every milking.

Cows had ad libitum access to water and a TMR delivered 3 times per day and pushed once per hour. During the close-up period, multiparous and nulliparous cows were fed a different diet. In addition, multiparous cows were subjected to another non-inferiority randomized controlled trial designed by the farm consulting team to examine the effect of feeding a close-up diet supplemented with a commercially available mineral binder (treatment diet group; sodium aluminosilicate, X-Zelit, Protetka) or a negative DCAD diet (control diet group) on the performance and health of cows during lactation. The close-up TMR provided to multiparous cows in the treatment diet group consisted of (DM basis) corn silage (51.1%), wheat straw (24.3%), canola meal (9.3%), soybean meal 47% (9.2%), X-Zelit (2.6%), molasses (1.3%), calcium carbonate (1.0%), and a dry cow mineral mix (1.2%). The close-up TMR provided to multiparous cows in the control diet group was the same as for the treatment diet group, except that it contained (all components included on a DM basis) commercial anionic salt (3.5%) and calcium carbonate (1.7%), whereas the dry cow mineral mix represented a smaller proportion of the TMR (0.9%). The close-up TMR provided to nulliparous cows consisted of (DM basis) corn silage (51.3%), alfalfa hay (13.7%), wheat straw (12.0%), canola meal (9.3%), soybean meal 47% (9.3%), molasses (2.6%), calcium carbonate (1.0%), magnesium oxalate (0.5%), and a dry cow mineral mix (0.3%).

The diets provided to cows in the fresh and high-producing pens were the same for primiparous and multiparous cows. The TMR provided to cows in the fresh pen consisted of (DM basis) corn silage (50.9%), dry corn meal (10.3%), canola meal (8.3%), soybean meal 47% (7.7%), cottonseed (6.8%), a lactating base mineral mix (5.9%), alfalfa haylage (5.7%), high-moisture shelled corn (2.9%), molasses mix (1.0%), and a fresh cow vitamin and mineral pack (0.5%). Finally, the TMR provided in the high-producing pen where cows were moved after leaving the fresh pen consisted of (DM basis) a high-producing premix (39.3%), corn silage (38.7%), alfalfa haylage (8.6%), high-moisture corn (6.6%), alfalfa silage (6.6%), and a high-producing cow vitamin and mineral pack (0.2%).

Automated Health Monitoring Systems

Nulliparous cows were fitted with a neck-attached automated behavior monitoring system (HR Tags; Merck & Co. Inc.) by research personnel at least 2 wk before the expected parturition date to provide enough time to establish a baseline for rumination time (**RT**) for each cow. Multiparous cows already had a functional tag fitted from the previous lactation. Sensor tag functionality was assessed weekly for individual cows until the end of the first 21 DIM through evaluation of rumination and activity data in the DataFlow system (DataFlow II Monitoring, Merck Animal Health). All cows enrolled in the experiment had a sensor regardless of experimental treatment group. Only cows that had a functional tag at all time points evaluated during the experiment were included in data analyses. Activity time (**AT**) and RT were

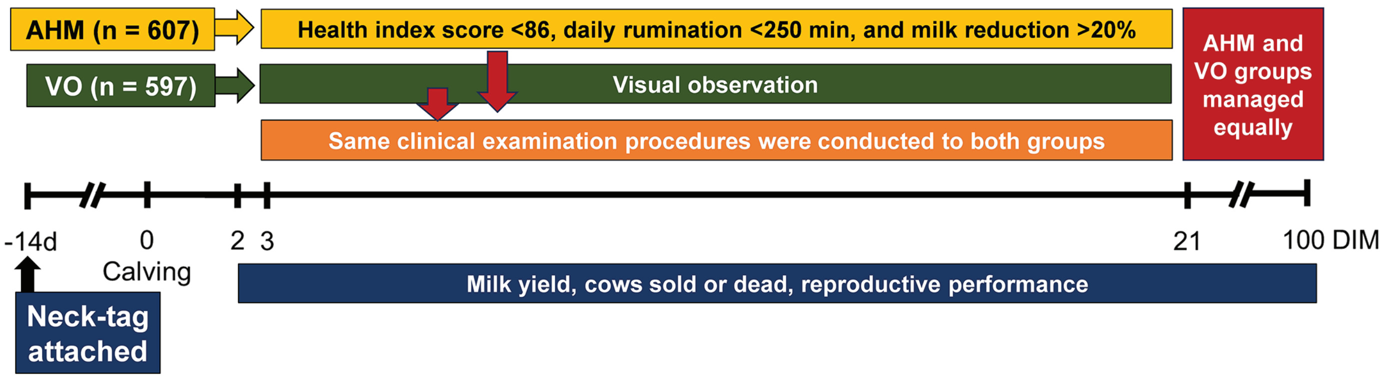

Figure 1. Graphical depiction of the experimental design for a randomized controlled trial that evaluated effects on the ability of detecting cows with health disorders and herd performance outcomes of a health monitoring program that selected cows for clinical examination from 3 to 21 DIM based only on visual observation (VO; n = 597) or based on alerts generated by automated health monitoring (AHM; n = 607) systems. A health alert was at least one of the following: a health index score <86 AU, daily rumination <250 min, or a reduction of >20% daily milk yield. Once selected for examination, the procedures used to diagnose health disorders were the same for both treatment groups. All cows were fitted with a neck-attached sensor tag of an automated behavior monitoring system at least 14 d before the expected date of parturition. From 2 to 100 DIM, herd exit, daily milk yield, and reproductive performance data were collected.

determined using internal algorithms. Rumination data were recorded in minutes per 2 h whereas activity data were recorded every 2 h but as an arbitrary number. Data from individual tags were transferred automatically to DataFlow every 20 min via antennas placed in the barns. Through a series of internal algorithms proprietary to Merck & Co. that used rumination data, activity data, or both for each cow, the system software generated a health index score (**HIS**; 0–100 arbitrary units [**AU**]) every 2 h. An HIS alert was defined as an HIS value of <86 AU for any 2-h period within a day. An HIS of 100 AU represents a cow with an ideal pattern of rumination and activity whereas an HIS value of <86 AU may be indicative that a cow is undergoing a health disorder. Custom-built reports were created by the research team to include cows with at least one HIS value <86 AU or daily rumination <250 min at any of the 2-h periods of each day.

Daily milk weights were recorded with individual stall milk meters (MM27BC, DeLaval) in 3 milking sessions ~8 h apart. The alert, created through custom-built commands in DairyComp305, was triggered when a reduction in MY >20% for the third milking session of the day (2100–2200 h) compared with the rolling average of the same milking session for the 7 previous days was detected.

During the study, farm personnel did not have access to reports or any data generated by the automated monitoring systems up to 21 DIM.

Experimental Treatments and Procedures for Selecting Cows for Clinical Examination

The experiment followed a randomized controlled trial design. Cows were enrolled at calving. Parity (primiparous vs. multiparous) and treatment group for the parous cows feeding trial during the close-up period (control diet vs. treatment diet) were used as blocking factors. Multiparous cows were also stratified by previous total lactation MY. No exclusion criteria were applied except for the absence of a functional sensor tag at calving. After blocking and stratification, the cohort of cows that calved on any given day (~18 cows/d) were randomly assigned to a health monitoring program that used VO (n = 597) or a program that used AHM alerts (n = 607) to select cows for clinical examination from 3 to 21 DIM (Figure 1). From calving to 2 DIM, cows from both groups (VO and AHM) were commingled in the same pens and managed equally. All cows regardless of treatment group were selected for clinical examination based exclusively on VO.

The experimental treatments differed only in the procedures used to identify and select cows for clinical examination. Cows in both experimental treatments were always commingled and managed equally except for the procedures used to select cows for clinical examination. During the experiment, the fresh pen housed an average of 389 cows.

VO Group

From 3 to 21 DIM, cows were selected for clinical examination exclusively through VO of clinical signs of disease during a daily walkthrough of the pens (fresh or high-producing). Visual observation of all cows enrolled in the experiment was conducted every day at ~0900 h by the first author (C.R.; a veterinarian with 6 years of experience and formal training in clinical examination and detection of health disorders in dairy cattle). Each cow housed in those pens underwent systematic observation. Visual observation of the cow front was used to evaluate general attitude (normal = alert, head and ears held up, eyes bright and no recession into the orbit, vs. depressed = unresponsive, droopy ears, sunken eyes, lethargic), nasal discharge (0 = normal serous discharge, 1 = minimal cloudy discharge, 2 = cloudy and excessive discharge, 3 = copious, bilateral mucopurulent nasal discharge), and abnormal breathing (shallow and rapid breathing), if present. Visual observation of the perineal area and udder was used to evaluate the presence of fetal membranes, vaginal discharge appearance (if present), manure consistency if the cow defecated (1 = watery, 2 = loose, 3 = thick porridge forming a pile of 2 to 3 cm, 4 = well-formed and stacks in rings, 5 = dry), and udder appearance if cows were standing (i.e., shape, color). All 4 legs were observed to determine inflammation of the hooves and signs of pain while walking if the cow was walking. A cow had to present at least one of the following to be selected for a clinical exam: depressed attitude; nasal discharge score >2; shallow or rapid breathing, or both; manure consistency scores of 1, 2, or 5; presence of fetal membranes; apparent signs of inflammation (i.e., redness, swelling) or pain in the udder; and abnormal vaginal discharge (red-brown, watery, fetid discharge). Cows selected for clinical examination were examined the next morning per the farm herd management procedures.

Although during the experiment all cows in the VO group had the sensor tag on, research and farm personnel who conducted experimental procedures were blind to the information generated by the automated monitoring system because data were not available in the custom-built reports provided by DataFlow. Because the person conducting VO was blind to the cow treatment group when conducting the walkthrough to identify cows for clinical examination, cows in the VO and AHM groups were observed, and their clinical signs of disease were recorded while in the pen. At the time of creating the list of cows for clinical examination for the next day, only cows in the VO treatment were included, and records for cows in the AHM group were discarded.

AHM Group

From 3 to 21 DIM, cows were selected for clinical examination only based on health alerts and data generated by automated monitoring systems (i.e., HR tags and daily milk weights). Cows were selected for clinical examination if an HIS <86 AU or daily RT <250 min occurred at any of the 2-h cycles for the 24 h period between the previous and the current time (0500 h) at which the list of cows for examination was created. Cows were also selected for clinical examination if they had a reduction in MY >20% for the third milking session of the day. Cows that met these criteria were considered to have an automated monitoring system alert.

The list of cows eligible for clinical examination in both treatment groups was created daily at ~0530 h by the first author (C.R.). This list included cows from the AHM group with alerts as described, cows from the VO group identified by VO the previous day as described, and cows previously diagnosed with a health disorder. The latter were examined every other day until the resolution of clinical signs. The identification number for all cows on the list was entered manually by pasting the number in the software of the sorting gates placed at the parlor exit.

The reason for selecting a cow for the clinical exam (i.e., VO of clinical signs of disease, health alert from the automated monitoring systems for cows in the AHM group, previous health disorder diagnosis, or combinations thereof depending on treatment group) was recorded. For cows selected for examination based on VO, the primary sign observed was also recorded (e.g., smelly vaginal discharge). For cows selected for examination based on alerts in the AHM, the type of alert that made the cow eligible for clinical examination was also recorded (e.g., RT <250 only, or a combination of milk deviation and HIS <86).

Clinical Examination and Application of Treatments

All procedures were conducted by 3 technicians unaware of experimental treatments assigned to cows. After the morning milking session, cows from the fresh pen included on the list for clinical examination were directed by 2 automatic sorting gates into a designated holding area. Cows not in need of an exam or other interventions returned to the fresh pen. Along with cows on the list for clinical examination for the experiment, other cows selected for interventions based on farm protocols (i.e., hoof trimming, cows suspected to have mastitis at milking) were directed to the same holding area. Once the fresh pen milking was completed, cows selected for experimental procedures (examination or treatment) or farm operating procedures, were moved to a special pen equipped with 100 self-locking headgates and used for examinations and management interventions. Due to cow commingling for experimental procedures and farm operating procedures, the number of cows present in this pen ranged from 21 to 75. The number of cows in the pen for experimental purposes ranged from 6 to 37, whereas the number of cows that underwent farm operating procedures ranged from 21 to 38.

Three technicians conducted all the experimental procedures. The team included the first author (C.R.) and 2 farm technicians trained in cow health monitoring procedures and supervised by C.R. Once all cows were restrained in self-locking headgates, 1 technician walked in front of cows on the feed lane. This technician identified cows using ear-tag numbers and indicated to the technician inside the pen conducting clinical examinations (C.R.) if a cow was eligible for a clinical exam or required a treatment based on a previous health disorder diagnosis. The technician in front of cows also evaluated cow attitude and interest in the TMR and recorded the outcomes of the clinical exam. Interest in the TMR was defined as a cow observed eating the TMR or evidence of eating based on the TMR surface (i.e., depression observed in the surface of the feed where a cow has eaten). All clinical exams, diagnoses of health disorders, and treatment decisions were conducted by the first author (C.R.). The third technician applied all treatments following farm defined treatment protocols. All 3 technicians were blind to treatment groups during the examination of cows. Blinding (or masking) was ensured by avoiding any marks or identification on the cows. All cows were housed together, and the technician who created the list of cows eligible for clinical examination (C.R.) had no access to the cows' IDs or the list of cows for examination.

Cows already diagnosed with health disorders receiving treatments that required milk withhold were moved to a hospital pen. These cows were subjected to the same procedures used for cows in the fresh pen. Cows identified with mastitis by milking technicians were diverted automatically to the hospital pen after milking. These cows only had their milk evaluated to confirm the case of mastitis, but no complete clinical exam was conducted on these cows unless they were included on the list of cows selected for examination based on the experimental procedures described for the VO and AHM treatment groups.

Once a cow was diagnosed with a clinical health disorder, the cow was sorted for examination every other day until the resolution of clinical signs. Cows with health alerts from the automated monitoring systems that were examined but were not diagnosed with a clinical health disorder underwent clinical examination every other day until no alert was observed or was diagnosed with a health disorder.

Cows selected for clinical examination underwent the same procedures regardless of treatment group and reason for examination (Figure 1). The first author (C.R.) conducted clinical examination for all cows. The examination included measurement of rectal temperature using an electronic thermometer (GLA M700, GLA Agricultural Electronics, San Luis Obispo, CA), evaluation of acetoacetic acid concentrations in urine (Ketostix, Ascensia Diabetes Care US Inc., Parsippany, NJ), and abdominal finger percussion to detect resonant areas as evidence of abnormal gas accumulation. Rectal palpation was conducted to evaluate rumen fill and obtain manure for determination of manure consistency, color, and odor. Vaginal and uterine discharge evaluation was conducted after rectal massage of the uterus and vagina to examine consistency, color, and odor of vaginal discharge. Palpation of the udder and milk fore stripping (milk was stripped onto the floor and observed for flakes or clots) was used to examine conditions affecting the udder.

In cows with pyrexia (rectal temperature ≥39.7°C), abnormal manure consistency (score 1, 2, or 5), Ketostix results different from negative, depressed attitude, or abnormal vaginal discharge (red-brown, watery, fetid discharge) during the clinical examination, abdominal and thoracic auscultation were conducted to examine primary ruminal movements and lung sounds, respectively. All cows with a urine ketone test outcome different from negative (trace = 5 mg/dL, small = 15 mg/dL, moderate = 40 mg/dL, and large = 80 to 60 mg/dL) had a blood sample collected for cow-side measurement of blood concentrations of BHB using BHB strips and a strip reading device (BHBCheck Plus, PortaCheck Inc.). Mastitis monitoring was also conducted during milking by milkers trained to identify signs of clinical mastitis (described with disorder definition). On average, a clinical exam with no treatment lasted ~1.5 min, whereas a clinical exam followed by treatment required 5 to 6 min.

From 22 to 100 DIM, cows from both treatment groups were managed equally. Cows were selected for clinical examination based on daily milk deviations >20% and HIS alerts using a threshold of <80 AU (farm operating procedure). Cows eligible for examination were sorted after milking and were examined by farm technicians only. The examination included abdominal finger percussion to detect resonant areas as evidence of abnormal gas accumulation, thoracic auscultation to examine the presence of abnormal lung sounds if needed, and rectal palpation to examine rumen fill and obtain manure for determination of manure consistency, color, and odor. Udder palpation and milk fore stripping onto the floor were used to identify signs of clinical mastitis.

Health disorder case definitions and application of treatments for health disorders are provided in Supplemental Tables S1 and S2, respectively (see Notes). The criteria used to define health disorders of interest were based on definitions adapted from Stangaferro et al. (2016a). Health disorders considered of interest for comparisons of the effects of the experimental treatments were clinical ketosis, displaced abomasum, indigestion, metritis, clinical mastitis, and pneumonia. Cases of indigestion, metritis, and mastitis were classified into severe and non-severe. Health disorders diagnosed and recorded but not of interest for comparisons of the effect of the experimental treatments were retained placenta, milk fever, lameness, and hyperketonemia diagnosed at 5

DIM based on farm operating procedures. The 3 clinical conditions were not included in analyses of the effects of the experimental treatments because these disorders are typically observed before 3 DIM, have a low incidence in the first 21 DIM, or both, and can be easily detected by VO. Hyperketonemia was not included because is subclinical condition.

For treatments that required milk or meat withhold, all required milk and slaughter withholdings were adhered to.

Reproductive Management

Cows were submitted for first service through a targeted reproductive management program. Cows received the sequence of hormonal treatments of the Double-Ovsynch protocol up to the third $PGF_{2\alpha}$ treatment (Pre-Ovsynch: GnRH, 7 d later $PGF_{2\alpha}$, 3 d later GnRH, 7 d later Breeding-Ovsynch: GnRH, 7 d later $PGF_{2\alpha}$, 1 d later $PGF_{2\alpha}$) when cows became eligible for AI at detected estrus (**AIE**) for 7 d. Cows not AIE within this 7-d period were submitted to an Ovsynch protocol with intravaginal progesterone supplementation (GnRH plus controlled internal drug release [**CIDR**] inserted, 7 d later $PGF_{2\alpha}$ and CIDR removed, 1 d later $PGF_{2\alpha}$, and 32 h later GnRH) for timed AI.

Inseminations at detected estrus were conducted 3 times per day after each of the milkings by 1 of 7 farm technicians, whereas timed AI was conducted only after the first milking (0530 to 1430 h) in cows that completed the synchronization of ovulation protocol for timed AI.

Pregnancy diagnosis was conducted every day of the week by farm personnel through transrectal ultrasonography of the uterine contents and ovaries (Ibex Pro, Ibex). The first pregnancy diagnosis was conducted at 30 d after AI and confirmation of pregnancy was performed at 50 d after AI. Pregnancy loss was recorded when a cow pregnant at the first examination was not pregnant on the day of confirmation of pregnancy or if the cow received AIE before pregnancy confirmation.

Herd Performance Outcomes Data Collection and Cow Grouping for Analysis

Data for herd performance outcomes collected from parturition until 100 DIM included daily MY, sales and deaths, inseminations, type of semen used (conventional beef or sexed semen), and outcomes of inseminations. Other events and cow features recorded included calving-related events (i.e., initiation of the lactation after an abortion, twin birth, stillbirth, and dystocia) and lactation number. Daily RT and AT data were collected up to 21 DIM.

For data analysis, cows were grouped retrospectively based on the diagnosis of health disorders through 21 DIM. Cows were included in a no clinical health disorder (**NCHD**) group if had no clinical health disorders diagnosed during the first 21 DIM. Cows in the clinical health disorder (**CHD**) group had at least 1 event of the clinical health disorders of interest diagnosed in the first 21 DIM (i.e., clinical ketosis, displaced abomasum, indigestion, metritis, mastitis, and pneumonia). Finally, a group of cows with clinical health disorders not included among the disorders of interest (i.e., milk fever, retained placenta or lameness) were grouped together for data analyses.

Sample Size Calculation

The sample size required was calculated with WinPepi v11.65 (Abramson, 2011) for a superiority trial with a specified margin of 7%, assuming that more cows would be diagnosed with health disorders (primary outcome of interest) in the AHM group than in the VO group (VO group = 23% [baseline proportion of cows with health disorders diagnosed at the experimental farm for the 12 mo before the beginning of the experiment]; AHM group = 30% of cows diagnosed with clinical health disorders). The probability of type I error rate was set at 5% and the probability of type II error was set at 20%. Based on these assumptions, 573 cows per group were needed to detect a statistically significant difference between treatments. To ensure that enough cows were enrolled to test hypotheses related to secondary outcomes of interest, additional sample size calculations were performed. The sample size required to detect a difference in mean RT of 20 min/d with an SD of 100 min (approximate SD for rumination time from 2 to 21 DIM using data from Stangaferro et al., 2016a) during the first 21 DIM when the ratio of sample size is 1:1 for both treatments and the type I and II error rates are 5% and 20%, respectively, was 394 cows per treatment. A total of 85 cows per treatment were needed to test the hypothesis that accumulated MY up to 21 DIM would be 31 kg (~1.5 kg/d) greater for the AHM treatment than for the VO treatment when the baseline MY for the VO group was 665 kg with an SD of 190 kg and the type I and II error rates were 5% and 20%, respectively. Mean and SD values for MY were estimated based on data for 1,656 cows that completed 21 DIM in the herd for the 12 mo before the experiment was conducted.

Statistical Analyses

All data analyses were conducted using SAS software version 9.4 (SAS Institute Inc., Cary, NC). Unless otherwise stated, models for all outcomes were developed and selected following the same methodology.

Descriptive statistics and frequency distributions for continuous data were generated with PROC MEANS and PROC UNIVARIATE. We examined normality of the data before analyses using graphical methods (histogram) and the Shapiro-Wilk test of normality generated by PROC UNIVARIATE. In addition, the normality of residuals and homogeneity of variance for all models with continuous outcomes were examined using residual plots. Univariable regression models built using PROC MIXED were used to examine associations between outcomes and potential covariates of interest including calving-related events; DIM at herd exit; hyperketonemia diagnosed at 5 DIM; a binary variable that indicated diagnosis (yes vs. no) of any of retained placenta, hyperketonemia, and lameness; and the type of semen used for first service. Variables with $P < 0.10$ in the univariate analysis were offered to multivariable models to evaluate outcomes of interest.

Unless otherwise stated, treatment group and blocking factors (i.e., parity and close-up period feeding trial groups) were forced in all models as fixed effects. The interactions between treatment and occurrence of health disorders, treatment and parity, and treatment and calving-related events were offered to models if the individual fixed effects covariates were also offered. Type of semen was offered as a covariate only in models for pregnancies per AI (**P/AI**). All covariates and interactions were removed by manual backward elimination if $P > 0.10$.

Previous lactation MY and the proportion of cows in each group of blocking factors (parity and close-up period diet groups [control diet vs. treatment diet]) were compared using ANOVA with PROC MIXED and logistic regression with PROC GLIMMIX to determine if allocation of cows to treatments was balanced.

Binary outcomes (percentage of cows that underwent clinical examination, percentage of cows diagnosed with clinical health disorders from 3 to 21 DIM and from 22 to 100 DIM, cows diagnosed with specific health disorders, cows that received treatment from 3 to 21 DIM, cows that were moved to the hospital pen, cows that left the herd [sold or died], P/AI at first service, and pregnancy loss) were analyzed using logistic regression with PROC GLIMMIX fitting a binomial distribution.

The incidence rate (**IR**) and incidence risk ratio (**IRR**) of CHD and clinical examination events to 21 DIM were compared as count data using Poisson regression with PROC GENMOD and a logarithmic transformation of time as the offset. A chi-squared test was used to assess model fit, and finally, simple effects of IRR estimates were calculated using the PLM procedure.

The daily patterns of MY (kg/d), RT (min/d), and AT (AU/d) were examined from 2 to 21 DIM by ANOVA with repeated measurements using PROC MIXED. Milk yield, RT, and AT recorded at 2 DIM were used as a baseline covariate. Similarly, the weekly average MY (average of daily MY for 7 d) was evaluated from 4 to 14 wk after parturition (i.e., from 22 to 100 DIM). Models for repeated measures analyses included the fixed effects of treatment, time (DIM or week), health disorder group (NCHD vs. CHD), and the treatment-by-time and treatment-by-time-by-health disorder group interaction. Days in milk at diagnosis of health disorders were forced in all models for evaluating patterns of RT, AT, and MY. Cow within treatment was included as a random effect in all models, and cow was the subject of repeated measurements. The covariance structure (compound symmetry, autoregressive order 1 with and without random effects, Toeplitz, and unstructured) were fitted to models for each response of interest. In all cases, Toeplitz minimized the Akaike information criterion and thus was selected as the covariance structure for all models.

The average RT, AT, and MY from 2 to 21 DIM for cows grouped based on the occurrence of each health disorder of interest (no, or yes = metritis, mastitis, DA, indigestion, clinical ketosis, and pneumonia) were analyzed with ANOVA using PROC MIXED. A dummy variable was created to be used as a covariate that adjusted for the effect of disorders other than the one being analyzed. A value of 1 for the dummy variable was assigned to all cows affected by any health disorder different from the one evaluated in the model of interest. For example, when analyzing the effect of metritis on RT, AT, and MY, cows that were affected by mastitis, DA, indigestion, clinical ketosis, and pneumonia received a value of 1 for the dummy variable.

Days in milk at clinical diagnosis of each disorder of interest, days in the hospital pen, DIM at first service, accumulated MY (sum of all daily milk values per cow per day the cow was present in the herd) from 2 to 21 DIM and from 2 to 100 DIM were analyzed by ANOVA using PROC MIXED.

Time to herd exit (sale or death) were analyzed using Cox proportional hazard regression models built with PROC PHREG. The assumption of proportionality of the hazards was visually assessed by plotting the logarithm of the negative logarithm of the survival probability by the logarithm of days at risk using PROC LIFETEST.

Results for count outcomes and proportions are presented as LSM and their 95% CI obtained using the LSMEANS statement of PROC GLIMMIX. Unless otherwise stated, data for continuous outcomes are reported as LSM and SEM or the 95% CI of the mean obtained using the LSMEANS statement of PROC MIXED. For some outcomes, arithmetic means and the SE obtained using PROC FREQ or PROC MEANS are also presented. Significance was declared at $P \leq 0.05$, and $0.05 < P \leq 0.10$ was considered a statistical tendency.

RESULTS

Out of all cows enrolled (n = 1,225), 21 had no functional tag either at calving (n = 16) or during the first 21 DIM (n = 5) and therefore were not eligible for enrollment or removed from the experiment. A small amount of missing data was observed for cows that remained in the experiment (n = 1,204). An average of 2.1% of all cow-days in the experiment had missing data.

We found no difference ($P = 0.85$) for the percentage of primiparous cows (VO = 29.3% [25.8%–33.1%]; AHM = 29.8% [26.3%–33.6%]) or cows enrolled in the treatment groups within the mineral binder ($P = 0.83$; VO = 35.1% [31.3%–38.9%]; AHM = 34.4% [30.7%–38.3%]) or DCAD ($P = 0.83$; VO = 64.9% [61.1%–68.7%]; AHM = 65.6% [61.7%–69.2%]) diet treatments. For multiparous cows, we found no difference ($P = 0.57$) for previous lactation total milk (VO = 12,739 ± 116 kg; AHM = 12,646 ± 116 kg). We found no difference between treatments ($P = 0.57$) in the proportion of cows with calving-related events (VO = 9.8% [7.4%–12.2%]; AHM = 10.2% [8.3%–13.2%]).

Data for the percentage of cows diagnosed with CHD diagnosed from calving to 2 DIM and diagnosed with CHD not of interest for analyses of the effects of experimental treatments from 3 to 21 DIM are presented in Supplemental Table S3 (see Notes).

Effect of Treatments on Clinical Examination Procedures and Detection of Cows with Clinical Health Disorders

More cows ($P < 0.001$) in the AHM (62.1% [58.8%–66.5%]) than the VO (28.8% [22.6%–29.6%]) treatment were selected for and underwent clinical examination at least once from 3 to 21 DIM, and cows in the AHM group (2.1 ± 0.5) had more clinical exams conducted ($P < 0.001$) than cows in the VO group (1.4 ± 0.6). As a result of the different dynamics generated to select cows for a clinical exam, 15.5 ± 3.4 and 5.3 ± 2.5 cows per day were included on the list for clinical examination for the AHM and VO treatment, respectively. The distribution of the number of times that cows in the VO and AHM treatment underwent clinical examination out of the cows that were examined at least once (VO, n = 172; AHM, n = 381) are presented in Supplemental Figure S1A and S1B, respectively (see Notes). The distribution of cows based on the primary clinical sign that led to a clinical examination for the VO treatment is presented in Figure 2A, whereas the distribution of cows based on the type of alert that led to selection for a clinical exam for cows in the AHM treatment is presented in Figure 2B. Out of the cows selected for clinical examination in the AHM group, 80.7% had alerts from the neck-attached behavior monitoring system only, 3.7% had milk deviation alerts only, and 15.6% had both types of alerts.

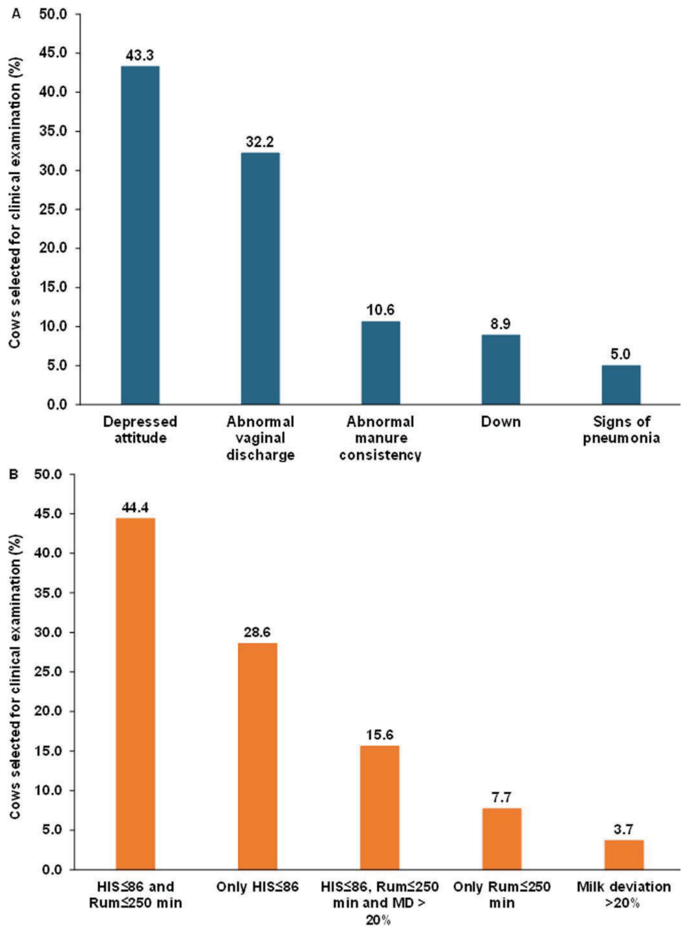

Figure 2. Distribution of cows grouped based on the primary reason used to select cows for clinical examination for cows randomly assigned to a health monitoring program that selected cows for clinical health examination from 3 to 21 DIM (A) based on visual observation of clinical signs of disease only (n = 172) or (B) based on alerts generated by automated health monitoring (n = 381) systems (neck-attached rumination and activity monitoring sensor and milk yield deviations based on daily milk weights). Down = cows in recumbency, HIS = health index score; Rum = rumination time.

Out of the cows examined in both treatments, 66.2% and 45.8% were diagnosed with at least one health disorder from 3 to 21 DIM in the VO and AHM treatments, respectively. The IR and IRR of cows selected for clinical examination, as well as cows identified with and without CHD by treatment, are presented in Table 1. The IR and IRR for the rate of cows examined, the rate of cows with

Table 1. Incidence rate and incidence rate ratio for clinical examinations and clinical health disorder diagnosis outcomes for Holstein cows randomly assigned to treatments that selected cows for clinical examination from 3 to 21 DIM using only VO (n = 597) or alerts from AHM (n = 607) systems in a randomized controlled trial[1]

	IR			IRR	
Outcome	VO	AHM	*P*-value	AHM-VO (Ref)	*P*-value
Rate of cows examined	0.033	0.090	<0.001	2.8	<0.001
Rate of cows with CHD/cow-day total	0.024	0.034	<0.001	1.4	<0.001
Rate CHD/cow-day examined	0.74	0.38	<0.001	0.51	<0.001
Rate NCHD/cow-day total	0.009	0.058	<0.001	6.5	<0.001
Rate NCHD/cow-day examined	0.26	0.62	<0.001	2.4	<0.001

[1]VO = visual observation; AHM = automated health monitoring; IR = incidence rate; IRR = incidence rate ratio; ref = referent; CHD = clinical health disorder (metritis, mastitis, displaced abomasum, clinical ketosis, indigestion, and pneumonia); NCHD = no clinical health disorder (cows without clinical health disorders).

CHD per cow-day total (count of all days that individual cows were at risk of being selected for clinical examination), the rate of NCHD diagnosed per cow-day total, and the rate of NCHD diagnosed per cow-day examined were greater ($P < 0.001$) for the AHM group than the VO group. Conversely, the rate of CHD diagnosed per cow-day examined was greater ($P < 0.001$) for the VO than the AHM treatment. Multiparous cows had greater risk of being subjected to clinical examination ($P < 0.001$) than primiparous, and cows with than without calving-related events had greater risk of undergoing clinical examination ($P < 0.001$).

More cows ($P < 0.001$) in the AHM treatment than the VO treatment were diagnosed with at least one health disorder from 3 to 21 DIM (Table 2). More cows in the AHM than in VO treatment were diagnosed with metritis, clinical ketosis, and indigestion (Table 2). Conversely, we found no difference between treatments in the percentage of cows diagnosed with mastitis, displaced abomasum, or pneumonia (Table 2). More cows were diagnosed with health disorders in the multiparous group ($P < 0.001$), the group with hyperketonemia ($P = 0.004$), and the group with calving-related events ($P < 0.001$). Days in milk at diagnosis of the first event of individual health disorders did not differ between treatments (Table 2). The IRR for all clinical health disorders diagnosis combined or for individual disorders was greater or tended to be greater for the AHM than the VO treatment for all the disorders except mastitis and pneumonia (Table 2).

No statistically significant difference between treatments was observed ($P = 0.50$) for the proportion of cows diagnosed with clinical health disorders (displaced abomasum, mastitis, indigestion, and pneumonia) from 22 to 100 DIM (VO: 16.1% [13.4%–19.7%] vs. AHM: 17.4% [14.3%–21.2%]).

Overall, more cows received at least one treatment for a clinical health disorder ($P < 0.001$) in the AHM (26.5% [22.5–29.4%]) than in the VO treatment (17.1% [14.7%–20.6%]). We found no differences in the proportion of cows with clinical health disorders that did not receive treatment ($P = 0.22$; VO: 6.6% [3.0–17.7] vs. AHM: 9.9% [7.4–16.8]). Out of the cows diagnosed with clinical health disorders that were not treated (n = 24), 66.6% had mastitis with a milk culture outcome of *Klebsiella* spp., *Escherichia coli*, or no growth, whereas the remaining 33.3% of the cows were either sold or died before treatment.

We found no difference ($P = 0.93$) between treatments for the number of days spent in the hospital pen (VO: 6.3 ± 0.6 d vs. AHM: 6.3 ± 0.5 d); however, more cows were

Table 2. Percentage of cows diagnosed with at least one clinical health disorder, DIM at diagnosis of the first clinical health disorder, and incidence rate ratio of clinical health disorder events for Holstein cows randomly assigned to be selected for clinical examination from 3 to 21 DIM using only VO of clinical signs of disease (n = 597) or alerts from AHM (n = 607) systems in a randomized controlled trial[1]

				DIM at diagnosis			IRR	
Outcome	VO, % (95% CI)	AHM, % (95% CI)	*P*-value	VO	AHM	*P*-value	AHM-VO (Ref)	*P*-value
CHD diagnosed	20.7 (16.2, 26.1)	35.5 (30.1, 41.3)	<0.001	—	—	—	1.6	<0.001
Metritis	8.0 (5.3, 11.8)	13.7 (10.3, 17.9)	0.02	6.9 ± 0.4	6.6 ± 0.5	0.19	1.5	0.05
Mastitis	3.3 (1.9, 5.7)	4.3 (2.6, 7.0)	0.38	7.0 ± 1.6	6.3 ± 0.8	0.71	1.3	0.39
DA	2.2 (1.1, 4.7)	3.1 (1.4, 6.6)	0.54	8.9 ± 1.6	7.2 ± 1.3	0.34	1.8	0.09
Indigestion	5.9 (3.9, 8.9)	12.3 (8.8, 16.8)	<0.001	5.8 ± 0.7	5.9 ± 0.6	0.88	2.0	<0.001
Clinical ketosis	4.1 (2.5, 6.6)	9.1 (6.3, 12.8)	0.001	7.7 ± 0.8	6.6 ± 0.5	0.17	2.2	0.001
Pneumonia	1.6 (0.6, 4.4)	3.0 (1.6, 5.4)	0.29	6.1 ± 1.9	5.9 ± 1.2	0.93	1.2	0.71

[1]VO = visual observation; AHM = automated health monitoring; IRR: incidence rate ratio; CHD = clinical health disorder (metritis, mastitis, displaced abomasum, indigestion, clinical ketosis, and pneumonia); DA = displaced abomasum.

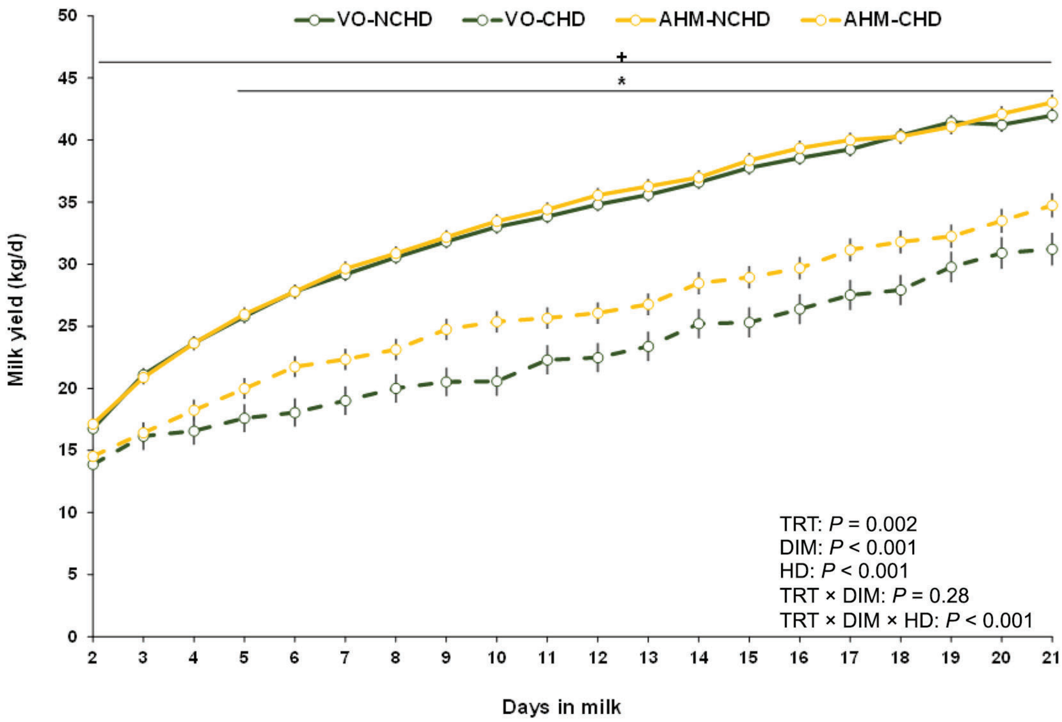

Figure 3. Least squares means and SEM for daily milk yield from 2 to 21 DIM for cows assigned to a health monitoring program that selected cows for clinical examination from 3 to 21 DIM only by visual observation of clinical signs of disease (VO; green lines) or by alerts generated by automated health monitoring (AHM; yellow lines) systems (neck-attached rumination and activity monitoring sensor and milk yield deviations based on daily milk weights) and were diagnosed with at least one clinical health disorder (CHD; dashed lines; VO-CHD: n = 89; AHM-CHD: n = 161) or were not diagnosed with CHD (NCHD; solid lines; VO-NCHD: n = 508; AHM-CHD: n = 446). TRT = treatment; HD = health disorder group (CHD vs. NCHD). Within a day, differences between groups based on the LSD test are represented as follows: *VO-CHD different from AHM-CHD; +VO-NCHD different from VO-CHD, AHM-NCHD different from AHM-CHD, AHM-NCHD different from VO-CHD, and VO-NCHD different from AHM-CHD.

sent to the hospital pen (P = 0.02) for the AHM group (15.8% [11.8%–20.1%]) than the VO group (10.7% [7.3%–14.3%]). Therefore, the total number of cow-days spent in the hospital pen was greater (P < 0.001) for the AHM (436 ± 3.4 d) than for the VO treatment (277 ± 4.7 d).

Milk Yield, Rumination Time, and Activity Time

Daily Milk Yield. We identified an interaction between treatment, DIM, and health disorder group for daily MY from 2 to 21 DIM (P < 0.001; Figure 3) because cows in the CHD group in the AHM treatment had greater MY than cows in the CHD group in the VO treatment from 3 to 18 and 20 to 21 DIM. No statistical difference was observed between treatments by DIM for cows in the NCHD group. We also found an interaction between treatment and CHD group (P = 0.05) whereby cows in the CHD group in the AHM treatment (24.4 ± 0.6 kg/d) produced more milk than cows in the CHD group in the VO (22.1 ± 0.7 kg/d) treatment, but no differences were observed between cows with NCHD in the VO and AHM treatments (VO = 30.7 ± 0.6 kg/d; AHM = 31.1 ± 0.7 kg/d). Regardless of treatment, cows in the NCHD group (33.2 ± 0.4 kg/d) had greater MY than cows in the CHD group (24.1 ± 0.6 kg/d) from 2 to 21 DIM. Overall, daily MY from 2 to 21 DIM was greater (P = 0.005) for cows in the AHM (27.8 ± 0.4 kg/d) than the VO (26.4 ± 0.5 kg/d) treatment. Cows had less MY if were in the group with calving-related events (P < 0.001); the group with retained placenta, milk fever, or lameness (P = 0.009); and in the primiparous group (P < 0.001).

Similarly, we identified an interaction (P < 0.001) between treatment, time (week), and health disorder group for average weekly MY from 4 to 14 wk postpartum (Supplemental Figure S2; see Notes). Cows in both treatments in the NCHD group had greater MY than cows in both treatments in the CHD group from 4 to 14 wk after calving. Cows had less MY from 4 to 14 wk after calving if in the calving-related events group (P < 0.001) and if in the primiparous cow group (P < 0.001).

Accumulated Milk Yield. We found an interaction between treatment and health disorder group (P = 0.009) for accumulated MY from 2 to 21 DIM. Cows in the NCHD group in the VO (560 ± 11.3 kg) and AHM (567 ± 11.5 kg) treatments did not differ, cows in the CHD group and AHM treatment (443 ± 13.6 kg) were intermediate, whereas cows in the CHD group and VO treatment had the lowest MY (394 ± 17.2 kg). Overall, the AHM treatment had greater accumulated MY than the VO treatment (P = 0.001; VO: 494 ± 11.8 kg vs. AHM: 522 ± 10.7 kg) and the NCHD group had greater MY than the CHD group (P < 0.001; NCHD: 597 ± 8.3 kg vs. CHD: 419 ± 10.6 kg). Cows had greater accumulated MY from 2 to 21 DIM if in the multiparous group (P < 0.001), the group without retained placenta, milk fever, or lameness (P < 0.001), and in the group without calving-related events (P < 0.001).

We found no effect of treatment on accumulated MY from 22 to 100 DIM (P = 0.96; VO: 3,041 ± 38 kg vs. AHM: 3,043 ± 35 kg). Multiparous cows produced more milk than primiparous cows (P < 0.001), and cows in the NCHD group produced more milk than cows in the CHD group (P < 0.001). Finally, we found no effect of treatment on accumulated MY from 2 to 100 DIM (P = 0.47; VO: 3,338 ± 51 kg vs. AHM: 3,370 ± 48 kg). Multiparous cows produced more milk than primiparous cows (P < 0.001), and cows without health disorders produced more milk than cows with health disorders (P < 0.001).

Daily Rumination Time. For daily RT from 2 to 21 DIM, we found an interaction between treatment, health disorder group, and DIM (P < 0.001; Figure 4A). From 2 to 13 DIM, RT for cows in the AHM treatment was greater for cows in the NCHD than the CHD group. The same was observed for cows in the VO treatment from 2 to 14 DIM. From 7 to 21 DIM (except at 20 DIM), cows in the AHM treatment and CHD group had greater RT than cows in the same group in the VO treatment. Finally, for cows in the VO treatment, RT was greater from 2 to 21 DIM for cows in the NCHD than the CHD group. Cows with calving-related events had less (P < 0.001) RT than cows without calving-related events, cows with hyperketonemia had less (P < 0.001) RT than cows without hyperketonemia, primiparous cows had less (P < 0.001) RT than multiparous cows, and cows that received the DCAD diet had less (P = 0.03) RT than cows that received the diet with mineral binder.

Daily Activity Time. For daily AT from 2 to 21 DIM, an interaction between treatment, health disorder group, and DIM was observed (P < 0.001; Figure 4B). From 2 to 17 DIM, cows in the NCHD group in both the AHM and VO treatment had greater AT than cows in the CHD group in the AHM treatment. Cows in the NCHD group in the VO treatment had greater AT than cows in the CHD group in the VO treatment from 2 to 21 DIM. Greater AT was also observed from 2 to 7 DIM and 17 to 20 DIM for cows in the CHD group in the AHM treatment than for cows in the CHD group in the VO treatment. Cows in the NCHD group in the AHM treatment had greater AT than cows in the CHD group in the VO treatment from 2 to 21 DIM. Cows with calving-related events had less (P < 0.001) AT than cows without calving-related events and primiparous cows had greater (P < 0.001) AT than multiparous cows.

Effect of Health Disorders on Average Daily MY, RT, and AT. The interaction effects between treatment and health disorder occurrence for each of the disorders of interest (metritis, mastitis, displaced abomasum, indigestion, clinical ketosis, and pneumonia) for the average RT, AT, and MY per day from 2 to 21 DIM are presented in Table 3. For most of the comparisons, there was or tended to be a significant interaction between treatment and health disorder group because in most cases, the greatest values for MY, RT, and AT were observed for cows in the NCHD group in the AHM treatment, and the lowest values were observed for cows in the CHD group in the VO treatment. Overall, values for cows in the NCHD group in the VO treatment and cows in the CHD group in the AHM treatment were intermediate but were greater for cows in the NCHD group in the VO treatment than for cows in the CHD group in the AHM treatment.

Herd Exit Dynamics

The effect of treatments on the percentage of cows that exited the herd (sold, died, or both combined) to 21 DIM, 22 to 100 DIM, and the total from 2 to 100 DIM is presented in Table 4.

Herd Exit to 21 DIM. A tendency for a greater (P = 0.06) proportion of cows were sold to 21 DIM for the VO than the AHM. No other statistical differences between treatments were observed for the percentage of cows that exited the herd up to 21 DIM. More multiparous than primiparous cows left the herd (P = 0.01), more cows with than without health disorders not of interest (milk fever, retained placenta or lameness) left the herd (P < 0.001), and more cows with than without health disorders of interest left the herd (P < 0.001). The hazard of leaving the herd during the first 21 DIM did not differ between the AHM and VO (referent) treatment (1.2 [0.7, 1.9]; P = 0.48). Mean time to herd exit up to 21 DIM was 20.5 d (20.2, 20.7) and 20.2 d (20.0, 20.5) for the VO and AHM treatments, respectively. Multiparous cows were at a greater risk of leaving the herd than primiparous cows (P = 0.02), cows with than without a health disorder not included among the disorders of interest were at greater risk of leaving the herd (P < 0.001), and cows in the CHD group were at a greater risk of leaving the herd by 21 DIM (P < 0.001).

Herd exit from 22 to 100 DIM. No effects of treatment on the proportion of cows that exited the herd from 22 to 100 DIM were observed. More multiparous than pri-

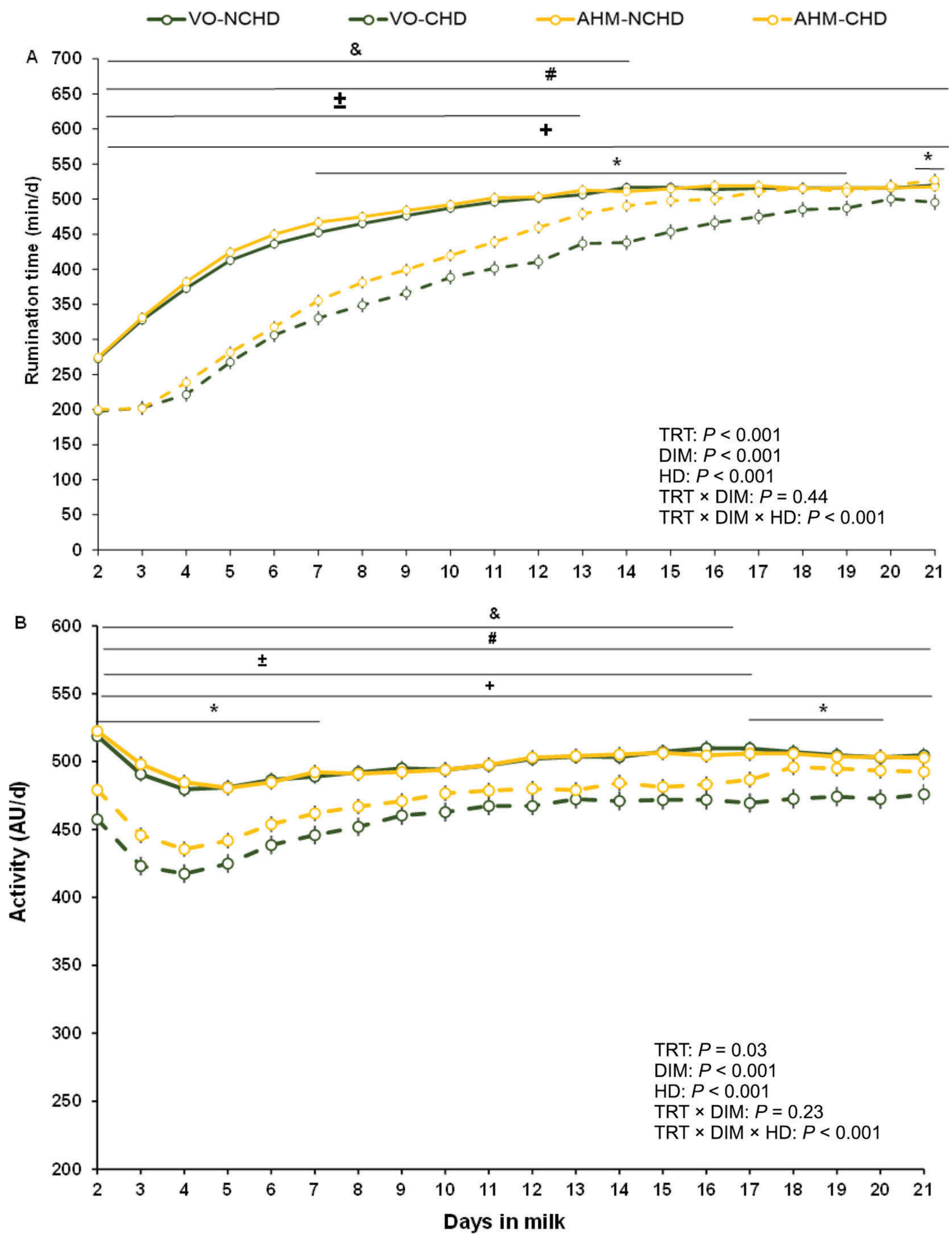

Figure 4. Least squares means and SEM for (A) rumination time and (B) activity time from 2 to 21 DIM for cows assigned to health monitoring programs that selected cows for clinical health examination from 3 to 21 DIM by only visual observation (VO; green lines) or by alerts generated by automated health monitoring (AHM; yellow lines) systems (neck-attached rumination and activity monitoring sensor and milk yield deviations based on daily milk weights), and were diagnosed with at least one clinical health disorder (CHD; dashed lines; VO-CHD: n = 89; AHM-CHD: n = 161) or no CHD (NCHD; solid lines; VO-NCHD: n = 508; AHM-CHD: n = 446) from 3 to 21 DIM. AU = arbitrary units; HD = health disorder group (CHD vs. NCHD); TRT = treatment. Within a day, differences between groups based on the LSD test are represented as follows: *VO-CHD different from AHM-CHD; +VO-NCHD different from VO-CHD; ± AHM-NCHD different from AHM-CHD; #AHM-NCHD different from VO-CHD; &VO-NCHD different from AHM-CHD.

Table 3. Least squares means and SEM for the interaction between treatment and clinical health disorder group for average daily MY, RT, and AT from 2 to 21 DIM; Holstein cows were randomly assigned to be identified for clinical examination from 3 to 21 DIM using only VO (n = 597) or alerts from AHM (n = 607) systems and grouped within treatment based on diagnosis of at least one clinical health disorder of interest (CHD) or not diagnosed with clinical health disorders (NCHD)[1]

	Group[2]				
Item	VO-NCHD	VO-CHD	AHM-NCHD	AHM-CHD	P-value
Metritis, n	561	36	551	56	
MY, kg/d	26.7 ± 0.2^{b}	19.5 ± 0.5^{d}	27.5 ± 0.2^{a}	22.3 ± 0.5^{c}	<0.001
Daily RT, min/d	437 ± 1.9^{b}	387 ± 4.8^{d}	444 ± 1.8^{a}	414 ± 3.9^{c}	<0.001
Daily AT, AU/d[2]	488 ± 0.9^{a}	461 ± 2.5^{c}	490 ± 0.9^{a}	475 ± 2.0^{b}	<0.001
Mastitis, n	579	20	581	26	
MY, kg/d	27.8 ± 0.2	19.7 ± 1.4	28.6 ± 0.2	23.2 ± 0.7	0.10
Daily RT, min/d	433 ± 1.8^{b}	345 ± 12.2^{d}	441 ± 1.7^{a}	400 ± 7.0^{c}	<0.001
Daily AT, AU/d	485 ± 0.9	476 ± 6.3	491 ± 3.6	487 ± 0.9	0.07
DA, n	589	10	588	19	
MY, kg/d	26.5 ± 0.2^{b}	13.7 ± 1.0^{d}	27.3 ± 0.2^{a}	21.9 ± 0.7^{c}	<0.001
Daily RT, min/d	442 ± 1.8^{b}	258 ± 8.8^{d}	449 ± 1.7^{a}	340 ± 6.6^{c}	<0.001
Daily AT, AU/d	489 ± 0.9^{b}	439 ± 4.6^{d}	492 ± 0.9^{a}	454 ± 3.4^{c}	0.04
Indigestion, n	562	35	532	75	
MY, kg/d	29.2 ± 0.3^{b}	16.6 ± 0.4^{d}	31.1 ± 0.2^{a}	19.5 ± 0.3^{c}	<0.001
Daily RT, min/d	445 ± 1.8^{b}	340 ± 4.8^{d}	450 ± 1.8^{a}	404 ± 3.4^{c}	<0.001
Daily AT, AU/d	488 ± 0.9^{a}	454 ± 2.5^{b}	489 ± 1.8^{a}	488 ± 0.9^{a}	<0.001
Clinical ketosis, n	572	25	552	55	
MY, kg/d	26.3 ± 0.2^{b}	18.7 ± 0.7^{d}	27.1 ± 0.2^{a}	23.3 ± 0.5^{c}	<0.001
Daily RT, min/d	442 ± 1.8^{b}	347 ± 6.4^{d}	449 ± 1.8^{a}	379 ± 4.3^{c}	<0.001
Daily AT, AU/d	488 ± 0.9^{b}	461 ± 3.3^{d}	491 ± 0.9^{a}	472 ± 2.3^{c}	0.03
Pneumonia, n	589	10	589	18	
MY, kg/d	25.8 ± 0.2	21.6 ± 1.1	26.7 ± 0.2	22.2 ± 1.0	0.79
Daily RT, min/d	431 ± 1.8^{b}	427 ± 10.4^{abc}	440 ± 1.8^{a}	401 ± 8.9^{c}	0.01
Daily AT, AU/d	486 ± 0.9	439 ± 5.2	489 ± 0.9	442 ± 5.3	0.97

[a–d]Different superscripts within a row indicate differences ($P \leq 0.05$) between means based on the LSD post hoc test.

[1]VO = visual observation; AHM = automated health monitoring; MY = milk yield; RT = rumination time; AT = activity time; AU = arbitrary units; DA = displaced abomasum.

[2]Cows within health disorder group either had the disorder listed only or the primary disorder plus another disorder of interest for the experiment at the same time or at some point from 3 to 21 DIM. The number of cows within treatment group with the primary disorder only versus the primary plus another disorder was: VO-CHD metritis only n = 20, VO-CHD metritis and another disorder n = 16; AHM-CHD metritis only n = 22, AHM-CHD metritis and another disorder n = 34; VO-CHD mastitis only n = 17, VO-CHD mastitis and another disorder n = 3; AHM-CHD mastitis only n = 20, AHM-CHD mastitis and another disorder n = 6; VO-CHD DA only n = 4, VO-CHD DA and another disorder n = 6; AHM-CHD DA only n = 5, AHM-CHD DA and another disorder n = 14; VO-CHD indigestion only n = 15, VO-CHD indigestion and another disorder n = 20; AHM-CHD indigestion only n = 29, AHM-CHD indigestion and another disorder n = 46; VO-CHD clinical ketosis only n = 5, VO-CHD clinical ketosis and another disorder n = 20; AHM-CHD clinical ketosis only n = 15, AHM-CHD clinical ketosis and another disorder n = 40; VO-CHD pneumonia only n = 6, VO-CHD pneumonia and another disorder n = 4; AHM-CHD pneumonia only n = 11, AHM-CHD pneumonia and another disorder n = 7.

Table 4. Least squares means (95% CI) for the percentage of cows that exited the herd (sold/dead) for Holstein cows randomly assigned to be identified for clinical examination during early lactation using only visual observation (VO; n = 597) or alerts from automated health monitoring (AHM; n = 607) systems from 3 to 21 DIM in a randomized controlled trial

Outcome	VO, % (95% CI)	AHM, % (95% CI)	P-value
Left herd to 21 DIM	11.5 (7.8, 16.7)	10.0 (6.9, 14.3)	0.54
Left herd from 22 to 100 DIM	9.2 (6.3, 13.3)	7.1 (4.9, 10.4)	0.26
Left herd to 100 DIM	21.6 (16.1, 28.1)	17.9 (13.4, 23.4)	0.22
Died to 21 DIM	1.7 (0.7, 3.9)	2.3 (1.1, 5.1)	0.31
Died from 22 to 100 DIM	2.6 (1.4, 5.1)	1.5 (0.7, 3.2)	0.28
Died to 100 DIM	2.5 (1.1, 5.3)	2.6 (1.2, 5.5)	0.82
Sold to 21 DIM	6.4 (4.1, 9.7)	3.3 (1.9, 5.5)	0.06
Sold from 22 to 100 DIM	7.8 (5.3, 11.4)	6.5 (4.4, 9.3)	0.48
Sold to 100 DIM	14.5 (10.7, 19.1)	10.4 (7.6, 14.0)	0.12

miparous cows ($P = 0.003$), and more cows ($P < 0.001$) in the CHD group than NCHD the group left the herd. No statistical differences between the AHM and VO (Ref) treatments (1.0 [0.9, 1.1]; $P = 0.80$) were observed for the hazard of herd exit from 22 to 100 DIM. Mean time to herd exit up to 100 DIM was 97.5 (96.7, 98.4) and 97.4 (96.4, 98.4) d for cows in the VO and AHM groups, respectively. Multiparous cows were at greater risk of leaving the herd than primiparous cows ($P = 0.02$), and cows in the CHD than the NCHD group were at greater risk of leaving the herd ($P < 0.001$).

Herd exit from 2 to 100 DIM. No statistical differences between treatments were observed for the percentage of cows that exited the herd to 100 DIM. More multiparous than primiparous cows left the herd ($P < 0.001$), more cows with than without the health disorders not of interest left the herd ($P < 0.001$), and more cows in the CHD group than the NCHD group left the herd ($P < 0.001$). The hazard of herd exit did not differ between the AHM and VO (Ref) treatments (0.9 [0.8, 1.1]; $P = 0.66$). Mean time to herd exit up to 100 DIM was 92.7 (90.9, 94.5) and 92.0 (90.1, 93.9) d for cows in the VO and AHM groups, respectively. Multiparous cows were at a greater risk of leaving the herd than primiparous cows ($P = 0.02$), cows with than without the health disorders not of interest were at a greater risk of leaving the herd ($P < 0.001$), and cows in the CHD group were at a greater risk of leaving the herd than cows in the NCHD group ($P < 0.001$).

Reproductive Performance at First Service

We found no difference between treatments for DIM at first service ($P = 0.78$; VO: 84.2 ± 0.5 vs. AHM: 84.1 ± 0.5). At 30 d after AI, first service P/AI were greater ($P = 0.04$) for the VO treatment (53.8% [47.5%–60.0%]) than the AHM treatment (47.2% [41.5%–52.9%]), cows in the CHD than the NCHD group ($P < 0.001$), primiparous than multiparous cows ($P = 0.05$), cows without than with calving-related events ($P = 0.03$), and cows inseminated with beef than cows inseminated with sexed semen ($P < 0.001$). At 50 d after AI, first service P/AI did not differ ($P = 0.19$) for the VO (48.5% [43.2%–51.7%]) and AHM (44.4% [39.3–49.8]) treatments, but were greater for cows in the CHD group than the NCHD ($P < 0.001$), for primiparous than multiparous cows ($P = 0.05$), for cows without than with calving-related events ($P = 0.03$), and for cows inseminated with beef semen than cows inseminated with sexed semen ($P < 0.001$). No difference in pregnancy loss ($P = 0.21$) was observed between treatments (VO: 9.6% [6.4%–13.7%] vs. AHM: 6.8% [4.3%–10.6%]), but more pregnancy losses were observed for multiparous than primiparous cows ($P = 0.01$), and for cows inseminated with beef semen than cows inseminated with sexed semen ($P = 0.006$).

DISCUSSION

This randomized controlled trial was designed to evaluate the effects on herd management and performance of a health monitoring strategy that relied exclusively on automated monitoring systems alerts to select cows for clinical examination. This strategy was compared with a health monitoring program that relied exclusively on VO of signs of disease to select cows for a clinical exam. In support of our hypothesis, cows in the AHM treatment had greater risk of being selected for clinical examination which resulted in more cows undergoing a clinical exam and diagnosed with health disorders. Moreover, for cows examined at least once, the number of exams received was greater for the AHM than the VO treatment group. A direct consequence of identifying more cows with health disorders was that more cows received treatments. The latter can help explain the greater overall MY of cows diagnosed with health disorders in the AHM treatment. More cows diagnosed and treated for clinical health disorders could also explain the reduced likelihood of herd exit due to sale during the first 21 d after calving.

Effects of Treatments on Herd Performance Outcomes

Increased MY from 3 to 21 DIM for only cows diagnosed with health disorders was the reason for the greater MY of the AHM treatment group. Enabling the positive effects of treatment on MY (Stangaferro et al., 2016a,b,c; Perez et al., 2020a,b; Rial et al., 2023a,b) by identifying more cows with health disorders, better timing of disease diagnosis, or a combination of both, are the most plausible reasons underpinning the differences in MY. This could not be confirmed or properly tested in this experiment because neither the true incidence of health disorders nor the onset of clinical signs of disease could be determined. Determining the true incidence of health disorders and the onset of clinical disease requires more intensive health monitoring strategies such as an exhaustive mandatory daily or more frequent clinical exam. Indeed, assuming equal underlying incidence of health disorders across treatments, the greater proportion of cows diagnosed with health disorders in the AHM treatment demonstrated that VO (i.e., as conducted in this experiment) by itself is insufficient to identify all cows affected by clinical health disorders. Underdiagnosis of disease was also possible for the AHM treatment. We previously reported a lower risk of health disorder diagnosis for an AHM program than for an intensive health monitoring program that included a combination of systematic daily clinical examination, daily MY deviation, and VO of all cows from 3 to 10 DIM (Perez et al., 2023). Other retrospective analyses of automated health alerts performance also reported that not all cows diagnosed with clinical health disorders had alerts immediately before or after clinical diagnosis of disease (Paudyal et al., 2016; Stangaferro et al., 2016a,b,c; Silva et al., 2021a).

Another factor that might have contributed to the observed difference in MY between treatments was the different time gap between selection for and execution of clinical examinations for the VO and AHM treatment. Per the farm standard operating procedures, cows could only be sorted for clinical exams and treatment once a day after the first morning milking session. In addition, it was not possible to conduct the pen walkthrough to select cows for examination before the milking session because of time constraints (i.e., should have been conducted before 5:00 a.m.) and concerns with disrupting cows before milking. Therefore, cows in the VO group were not examined immediately after observation of clinical signs of disease. Delayed diagnosis and treatment could, therefore, not be ruled out as contributors to the lower MY of cows in the CHD group in the VO treatment. As the association between time from observation of clinical signs of most health disorders and clinical examination on MY and other herd performance outcomes is unknown, the effect of the time gap from observation to examination in our experiment cannot be determined. Although the management constraints imposed on the VO treatment at this commercial farm might be herd specific, a similar scenario might be observed in dairy herds in which health monitoring routines are implemented on groups of cows rather than on individuals (Espadamala et al., 2016; Kerwin et al., 2022; Perez et al., 2023). Under such conditions, the ability to create lists of cows potentially affected by health disorders at any time of the day is another benefit of automated health monitoring systems over strategies that rely exclusively or almost exclusively on once a day or infrequent VO for identifying cows for a more detailed clinical examination.

The effects of the VO and AHM treatments on the population dynamics of the NCHD and CHD groups were evident in the comparisons of daily RT, AT, and MY from 2 to 21 DIM for cows affected by each health disorder of interest. In general, cows not diagnosed with health disorders (i.e., NCHD group) in the AHM treatment had the greatest RT, AT, and MY, followed by the same group of cows in the VO treatment. On the other hand, for most disorders, cows affected and in the AHM treatment had greater RT, AT, and MY than cows affected by the disorders but in the VO treatment. A plausible explanation for these observations is that the AHM treatment shifted the population dynamics of the CHD group, diverting more cows with less severe cases of some diseases, such as metritis and indigestion, to this group (Supplemental Table S4; see Notes). Through an increase in the representation of cows with less severe cases of health disorders in the CHD group, the AHM treatment could have had a 2-fold effect on MY. On one end, the magnitude of the reduction in MY due to disease is less in cows with non-severe cases of health disorders (Stangaferro et al., 2016b,c; Rial et al., 2023a,b). On the other hand, treating cows with less severe cases of health disorders could have had a positive effect on MY because prompt treatment could have prevented an increase in the severity of disorders, the development of another disorder that affects MY, or both. Moreover, prompt treatment in cows with less severe cases of a disorder might also have resulted in a better treatment response, minimizing the reduction in MY due to disease or an earlier return to a positive trajectory of milk production (McArt et al., 2012). Ultimately, the collective effects of altering the composition of the CHD and NCHD groups and the positive effects of treatment on more cows in the CHD group in the AHM treatment must have synergized, increasing overall milk production for the AHM treatment.

Health disorders during early lactation have a strong influence on the exit dynamics of a herd because cows with poor MY and reproductive performance and cows at greater risk of developing other health disorders throughout lactation are more likely to be removed (Ribeiro et al., 2016; Stangaferro et al., 2016c; Carvalho et al., 2019). In agreement with previous reports (Probo et al., 2018; Carvalho et al., 2019; Pinedo et al., 2020b), cows diagnosed with health disorders during early lactation in both treatment groups were at greater risk of sale and death, had reduced MY, and had poorer reproductive performance compared with cows not diagnosed with health disorders. Having records of health disorders in early lactation can also increase the risk of herd exit later in lactation. Indeed, Silva et al. (2021a) reported that adding automated monitoring systems alerts to a health monitoring program including mandatory clinical examination resulted in more cows treated for health disorders and a greater risk of herd exit due to sale. On the contrary, despite the increased risk of health disorder diagnosis, the AHM treatment had ~50% fewer cows sold in the first 21 DIM. The most likely explanation for this effect was that greater MY for cows with health disorders in the AHM treatment protected these cows from herd removal, as milk production level is an important criterion for herd exit decision-making (Gröhn et al., 1998; Hadley et al., 2006; Pinedo et al., 2010). This was the case for the herd where the experiment was conducted, as 44% of the cows sold in the VO treatment were coded as "low production" compared with 24% of the cows in the AHM treatment (Supplemental Table S5; see Notes). Therefore, health monitoring strategies that identify more cows with health disorders could reduce cow sales due to low MY through the positive effects of improved health on milk production.

Identifying and providing treatment for health disorders (Dubuc and Denis-Robichaud, 2017; Silva et al., 2021b) might reduce the magnitude of the detrimental effects of health disorders in early lactation on reproduction (Fonseca et al., 1983; Carvalho et al., 2019; Pinedo et al., 2020a). This is especially relevant for metritis because despite a high rate of self-cure in affected cows (Chenault et al., 2004; McLaughlin et al., 2012; de Oliveira et al., 2020), antimicrobial treatment for metritis can improve group-level reproductive outcomes (Drillich et al., 2001; de Oliveira et al., 2020). In this experiment, we observed no benefit of identifying and treating more cows for all health disorders combined on first service P/AI and pregnancy loss. Notably, this was observed despite identifying and treating ~70% more cows with metritis in the AHM than the VO treatment and observing a negative association between occurrence of health disorders and P/AI at 30 and 50 d after AI. Embryo development before placental attachment is impaired in cows with nonuterine and uterine diseases (Ribeiro et al., 2016). Therefore, if cows affected by health disorders in the VO treatment were more likely to be left untreated due to underdiagnosis, the greater P/AI at 30 d after insemination for this group cannot be easily explained. The lack of a difference in P/AI at 50 d after AI was more in line with expectations and suggested that the magnitude of the effect of not diagnosing and treating some cows with clinical health disorders was insufficient to affect reproductive performance at the group level. For cows affected by metritis, which is more directly associated with fertility than other diseases (Ribeiro et al., 2016), it is possible that many cows not diagnosed had reasonable reproductive performance because of self-cure (McLaughlin et al., 2012; Sannmann et al., 2013; de Oliveira et al., 2020). Alternatively, the proportion of cows with other clinical diseases or metritis that were not treated and remained in the herd until first service might not have been sufficiently large to reduce P/AI at the group level. These equivocal results for first service reproductive outcomes for cows in the VO and AHM treatments warrant further investigation of the effects of health monitoring and management in early lactation on reproductive performance.

In previous studies, automated monitoring systems alerts and data were incorporated into health monitoring strategies for dairy cows. Silva et al. (2021a) evaluated the effect of adding automated health alerts from the same neck behavior monitoring sensor used in this experiment to a traditional health monitoring program based on mandatory clinical exams at 3, 5, and 9 DIM and daily MY deviations. Because no differences were observed between treatments in the proportion of cows that left the herd, total MY up to 22 wk postpartum, or reproductive performance, adding health alerts from an automated monitoring system to a relatively intensive health monitoring program did not have major positive or negative effects on herd performance. Similarly, Perez et al. (2023) conducted a randomized controlled experiment to evaluate herd level effects of a health monitoring program designed to rely primarily, but not exclusively on alerts from automated monitoring systems. This program was compared with a combination of systematic clinical examination of all cows during the first 10 DIM, use of MY reduction alerts, and VO. Despite a reduced risk of diagnosis of health disorders, the program that relied primarily but not exclusively on automated health alerts did not negatively affect MY, herd exit risk, and first service reproductive performance. These 2 experiments (Silva et al., 2021a; Perez et al., 2023) demonstrated that relying primarily on automated alerts or complementing traditional intensive health monitoring programs with automated alerts could be at least as effective as intensive traditional health monitoring programs. On the other hand, the current experiment is the first to demonstrate that the use of a health monitoring strategy that relies exclusively on automated monitoring systems to select cows for clinical examination can increase the proportion of cows diagnosed with health disorders in early lactation and improve herd performance compared with a non-intense health monitoring strategy that uses VO only to select cows for clinical examination.

Collectively, these results demonstrated the benefits and drawbacks of health monitoring strategies based on AHM systems alerts versus the use of VO only. Increased labor and disruption of cow routines are undesirable consequences of conducting more clinical exams and diagnosing more cows with clinical health disorders when using AHM health alerts rather than only VO. Nevertheless, these drawbacks might be fully offset by valuable positive effects on herd performance, such as increased milk production and a reduced likelihood of herd exit.

Effects of Treatments on Health Monitoring and Management

A direct effect of using automated health alerts rather than VO for selecting cows for clinical examination was the diagnosis of more cows with clinical health disorders. The disorders for which a difference in diagnosis risk and proportion of cows diagnosed was observed were those characterized by presenting a wider range of severity and diversity of clinical signs. Specifically, metritis, indigestion, and clinical ketosis were more frequently diagnosed in the AHM treatment than the VO treatment. This is in line with the fact that milder cases of these disorders tend to have less of an impact on behavioral parameters than more severe cases. For example, metritis defined as the inflammation of the uterus can be manifested with or without evident systemic signs of disease (Sheldon et al., 2006). Therefore, some less severe cases of metritis with no systemic signs of disease may have been diagnosed because of the mandatory evaluation of uterine discharge and the examination of the uterus in all cows that underwent clinical examination. Similarly, clinical signs that are more difficult to assess, such as a reduction in ruminal movements and diarrhea, were among the signs included in the definition of clinical ketosis and indigestion. As for metritis, there could have been a bias (regardless of treatment group) on the diagnosis of clinical ketosis and indigestion because the clinical exam conducted in all cows included the evaluation of ruminal movements and manure consistency. Thus, the simple fact that more cows were selected for clinical examination and physiological parameters and bodily fluids were evaluated in all cows that underwent a clinical exam could explain, at least in part, the increased incidence of metritis, clinical ketosis, and indigestion in the AHM treatment.

We found no differences in the IRR and the proportion of cows identified with displaced abomasum, pneumonia, or mastitis. Cows affected by these disorders tend to have alterations of their general attitude that are more easily recognized by VO. Altered attitude is one of the clinical signs most used by commercial farms to select cows for clinical examination (Kerwin et al., 2022), and in this study, it was the most common reason to select cows for clinical examination in the VO group. Cows affected by displaced abomasum tend to be dehydrated due to the sequestration of hydrochloric acid into the abomasum, which attracts water (Rohn et al., 2004; Mokhber Dezfouli et al., 2013). Therefore, altered attitude with sunken eyes is characteristic of some cases of this disorder. Cows with pneumonia have depressed attitude, nasal discharge, lethargy, and increased respiratory rate (Ferraro et al., 2021), which are signs easily detected by VO. Cows affected with severe or toxic mastitis also have notable alterations of their behavior, which are easily detected by the behavior monitoring sensor and VO (Stangaferro et al., 2016b; Rial et al., 2023b). Most of the milk samples from cases of severe mastitis observed in this experiment in early lactation resulted positive for *E. Coli* and *Klebsiella* spp. which in many cases lead to systemic signs of illness due to endotoxemia (Siivonen et al., 2011; Fogsgaard et al., 2012; Ginger et al., 2023). The latter include dehydration and depressed attitude, which are also easily detected by VO (Foley and Schlafer, 1994). Collectively, the typical manifestation of displaced abomasum, mastitis, and pneumonia could explain the similar proportion of cows diagnosed with these disorders for the VO and AHM treatment.

Even though we found no difference in the average number of days that cows spent in the hospital pen, a greater proportion of cows from the AHM group were in the hospital pen due to treatment. As a result, the total number of cow-days spent in the hospital for the AHM group was greater than for the VO treatment. This is undesirable because sending more cows to the hospital pen can result in more discarded milk or more milk being diverted to other uses for which milk has less value than saleable milk (e.g., calf feeding). Ultimately, more discarded milk could reduce farm income and offset the value of finding more cows with health disorders and increasing milk production due to improved health when using AHM. Thus, the effects on dairy herd economics of implementing automated health monitoring and management programs such as the one evaluated in this experiment must be explored.

The greater proportion of cows in the AHM than the VO treatment that underwent clinical examination but were not diagnosed with a health disorder from 3 to 21 DIM suggested that the criteria used to generate alerts might have been too sensitive or the health alerts used were caused by conditions not manifested through the clinical signs used as criteria for disease diagnosis in this experiment. Thus, the health alerts for cows with no evident clinical signs of the specific diseases monitored could have been the result of subclinical conditions, other disorders not evaluated, or false positive alerts. Unfortunately, the nature of these alerts could not be determined because neither subclinical conditions nor other disorders which could affect cows were systematically evaluated. Of note, based on a retrospective analysis, cows with health alerts but no clinical health disorders diagnosed had less MY, RT, AT, and HIS than cows with no health alerts and no clinical health disorders diagnosed (data not shown). These observations suggested that these cows might have undergone conditions without clinical manifestation but that were capable of affecting cow productivity and behavior. A better understanding of the sensor data patterns and underlying biology of cows with automated health alerts, but no evident clinical signs of disease, is necessary in order to develop strategies to manage these cows, improve health alert algorithms, or both. For example, although the most common reason for selecting cows for clinical examination in the AHM treatment was the combination of HIS and raw rumination, most of the alerts for cows not diagnosed with clinical health disorders were due to raw rumination <250 min alone, and most instances were observed from 3 to 5 DIM (data not shown). The most likely explanation for these observations is the large cow-to-cow variation for absolute rumination time and variability in the rate of increase in RT immediately after parturition (Calamari et al., 2014; Borchers et al., 2017). Indeed, RT as reported by automated wearable sensors does not reach a plateau until the second or third week after parturition (Soriani et al., 2012; Calamari et al., 2014; Liboreiro et al., 2015). Thus, the criteria we used to select cows for clinical examination could be refined to maximize the proportion of cows identified with health disorders and reduce the number of clinical exams. For example, selecting cows for clinical examination before 5 DIM using an RT threshold <250 min could help reduce the number of putative false positive alerts. Future studies should attempt to elucidate the underlying reasons for observing cows with automated health alerts but no overt clinical signs of disease. A better understanding of this phenomenon could help to develop strategies to mitigate potential frustrations with on-farm use of these technologies. For example, algorithms or mathematical functions used to trigger alerts could be adjusted to achieve desired levels of sensitivity and specificity. Alternatively, cows with automated health alerts and no clinical signs of disease might be affected by subclinical conditions or other conditions (e.g., health disorders not evaluated in this experiment) that affect health and performance sufficiently as to justify the use of interventions to prevent clinical disease or further reductions in performance.

Experiment Limitations

Noteworthy limitations of this experiment included lack of external validity, not fully characterizing the true incidence of health disorders, the inability to confirm or rule out other clinical or subclinical health disorders that could have affected cow health and the parameters monitored by the automated monitoring systems, and restrictions on the implementation of clinical exams due to herd management constraints. Conducting the experiment at a single farm limited external validity but enabled proper execution of the experimental procedures of a randomized controlled trial with cows in both treatments under the exact same management and environmental conditions. External validity was also limited because a single technician conducted all visual observation procedures and clinical examinations, and because the procedures used to select cows for examination for the VO treatment might be unique to the farm where this experiment was conducted. The procedures used to select cows for examination for the AHM treatment might have also been unique to this experiment and might not reflect the procedures used to select cows for examination at other commercial farms. Not characterizing the true incidence of health disorders in a third group of cows did not allow comparing the performance of the VO and AHM to a referent. Moreover, establishing the true incidence of health disorders for the VO and AHM treatment groups was not possible without biasing the procedures to diagnose disease. Ruling out or confirming other clinical and subclinical disorders not monitored would have required a more exhaustive clinical exam and complimentary tests that could not be conducted under the experimental conditions of this large commercial dairy farm. The reasoning and consequences of the different time gap between selection for and execution of the clinical exams in the VO and AHM treatment were discussed in detail and should be considered for future experiments comparing automated versus non-automated health monitoring strategies.

CONCLUSIONS

We concluded that implementation of a health monitoring program for early lactation cows that relied exclusively on automated monitoring systems alerts based on RT, activity, and MY for selecting cows for clinical examination might be a more effective strategy to identify cows with CHD than the use of VO alone. Using automated health alerts resulted in more clinical examinations, which led to more cows diagnosed with health disorders and more treatments. This led to greater MY and reduced likelihood of sale during the first 21 DIM. A caveat of using alerts from AHM systems might be the examination of cows with no overt clinical signs of disease. Thus, more research is needed to elucidate the underlying reasons for these alerts in cows with no evident clinical signs of disease and their effects on herd health monitoring and management practices. Although some of these alerts might be false positive outcomes, it is also possible that these alerts are an indication of conditions that affect cow performance, health, and well-being that can be resolved or prevented through proper interventions.

NOTES

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Nonstandard abbreviations used: AHM = automated health monitoring; AIE = AI at detected estrus; AT = activity time; AU = arbitrary unit; CHD = clinical health disorder; CIDR = controlled internal drug release;

DA = displaced abomasum; HD = health disorder group; HIS = health index score; IR = incidence rate; IRR = incidence risk ratio; MY = milk yield; NCHD = no clinical health disorder; P/AI = pregnancies per AI; ref = referent; RT = rumination time; TRT = treatment; VO = visual observation.

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