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On the use of physical activity monitoring for estrus detection in dairy cows

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ABSTRACT

Detection of estrus in dairy cattle is effectively aided by electronic activity tags or pedometers. Characterization of estrus intensity and duration is also possible from activity data. This study aimed to develop an algorithm to detect and characterize behavioral estrus from hourly recorded activity data and to apply the algorithm to activity data from an experimental herd. The herd comprised of Holstein (n = 211), Jersey (n = 126), and Red Dane (n = 178) cattle, with virgin heifers (n = 132) and lactating cows in the first 4 parities; n = 895 cow-parities, with a total of 3,674 activity episodes. The algorithm was based on deviations from exponentially smoothed hourly activity counts and was used to identify onset, duration, and intensity of estrus. Learning data included 461 successful inseminations with activity records over a 2-wk period before and after the artificial insemination. Rates of estrus detection and error rate depended on the chosen threshold level. At a threshold giving 74.6% detection rate, daily error rate was 1.3%. When applied to a subset of the complete data where milk progesterone was also available, concordance of days to first activity-detected estrus with the similar trait based on progesterone was also dependent on the chosen threshold so that, with stricter thresholds, the agreement was closer. A single-trait mixed model was used to determine the effects of systematic factors on the estrus activity traits. In general, an activity episode lasted 9.24 h in heifers and 8.12 h in cows, with the average strength of 1.03 ln units (equivalent to a 2.8-fold increase) in both age groups. Red Danes had significantly fewer days to first episode of high activity than Holsteins and Jerseys (29.4, 33.1, and 33.9 d, respectively). However, Jerseys had significantly shorter duration and less strength of estrus than both Red Danes and Holsteins of comparable age. The random effect of cow affected days to first episode of high activity and strength as well as estrus duration. Days from calving to first episode of high activity correlated negatively with body condition scores in early lactation. The results suggest that data from activity monitors could supply valuable information about fertility traits and could thereby be helpful in management of herd fertility. To establish the complementarities or interdependence between progesterone and activity measurements, further studies with more information from different sources of measuring estrus are needed.
Key words: activity meter, pedometer, estrus, first episode of high activity

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INTRODUCTION

Female fertility may be defined in several ways that commonly address the ability of a given cow to get pregnant. This trait has 2 parts. The first part deals with the cow cycling and showing estrus. The second part is about getting the cow pregnant following an insemination. Fertility traits can be expressed as days open, calving interval, and number of AI services needed before pregnancy. One important fertility trait is that which expresses the commencement of luteal activity. Luteal activity is defined as the time when progesterone concentration first exceeds a set threshold of, for example, 3 ng/mL (Bulman and Lamming, 1978). Traits such as period from calving to luteal activity (**C-LA**) have been proposed as indicators of fertility (Royal et al., 2002; Petersson et al., 2007). The traditional way to determine C-LA is through the use of progesterone profiles. The setback is that progesterone measurements are not readily available as routine measurements on farm. The increase in the use of herd management devices invented for detection of estrus on farm provides an opportunity for the use of information generated by the physical activity meters for determination of days to first episode of high activity (**DFHA**) as a substitute for C-LA or days to first estrus (Løvendahl and Chagunda, 2006). This idea was initially suggested in an experimental study by Løvendahl and Chagunda (2006) and is further pursued here.

Electronic pedometers or activity tags use changes in behavior to detect estrus in dairy cows and heifers. Restlessness and general physical activity increase markedly during estrus (e.g., Farris, 1954; Van Eerdenburg et al., 1996). Other changes in behavior, such as standing heat and mounting behavior, are the known behavioral identifiers of estrus. Most pedometers and activity tags are designed to identify the restlessness and elevated physical activity of cows (e.g., Lactivator, Nedap Agri BV, Groenlo, the Netherlands; Alpro, DeLaval, Tumba, Sweden). Other automated systems for detection of mounting behavior are available in the form of color ampoules (Kamar, Kamar Inc., Steamboat Springs, CO) and electronic devices (HeatWatch, Cow Chips LLC, Manalapan, NJ). Estrus detection based on activity measurements requires dedicated software supplied as part of farm-management systems (e.g., AlproWin, DeLaval) that come with the activity detectors as a complete package. Algorithms for detection of estrus are part of the software and usually not available to buyers. Theoretical work on detection algorithms (De Mol and Woldt, 2001; Firk et al., 2002; Roelofs et al., 2005b) shows that detection efficiency varies greatly depending on the complexity of the method. The efficiency of the various types of devices in terms of estrus detection rate has been reported to be between 50 and 100%, depending on criteria of success and methods of determining the signal and its interpretation (At-Taras and Spahr, 2001).

This study aimed to develop an algorithm to detect and characterize behavioral estrus from hourly recorded activity data (DFHA and duration, strength, and regularity of activity periods based on activity tag records) and to apply the algorithm to activity data from an experimental herd. In turn, the systematic influence from various fixed management factors and sources of random variation were studied.

MATERIALS AND METHODS

Animals and Study Design

The study was based on activity tag records for heifers and cows in the experimental herd at the Danish Cattle Research Centre (**DCRC**), Tjele, Denmark. The animals were equipped with activity tags as part of the management routine for cows in order to facilitate heat detection. Records taken on the animals included visual estrus scores, AI service, pregnancy check, calving dates, milk progesterone-based C-LA, and repeated BCS for cows. Approval of the experimental protocol by the animal care and use committee was not needed because this experiment used only data recorded from standard commercial farm equipment.

The DCRC herd included cows of 3 breeds: Jersey, Holstein, and Red Dane. The herd was divided into 3 groups, each assigned to an automated milking system (VMS, DeLaval). Two groups, Holstein and Red Dane, consisted of 55 cows each. The third group consisted of 42 Jersey cows. Cows were housed year-round and fed TMR ad libitum with supplementary concentrates during milking in the VMS. The VMS were always open for milking except during 2 periods of approximately 1 h for wash cycles. Milking cows were of mixed parities, although priority was given to young cows at times of replacement. The current study was restricted to cows of parities 1 to 4. Heifers (parity 0) were housed in pens holding up to 12 heifers at any one time. Heifers were fed TMR ad libitum. Recording of activity data for this study was initiated in July 2001 and closed in December 2008. Activity tags for heifers were acquired later; hence, recording of heifers commenced in February 2004.

Reproduction and AI Protocol

The reproduction strategy at DCRC aimed to initiate AI at first estrus after 15 mo of age in Holstein and Red Dane heifers, and at 13 mo in Jersey heifers. Postpartum AI commenced at 35 DIM and was repeated until a pregnancy was established. Artificial induction of estrus was used if heat had not been detected at 120 DIM. Pregnancies were confirmed using palpation at 35 d after AI. Estrus detection was carried out using a combination of visual observations and use of activity records through the AlproWin management software (DeLaval). Farm staff using an established protocol conducted the visual observations twice daily. In brief, the protocol stipulated that visual signs be scored on a binary scale (on vs. off) based on secretion of clear mucus, swelling and reddening of vulva, mounting on others, receiving mounting from others, and typical estrus behavior including at least one of the following: licking, vocalizing, hyperactivity, and friendly contact with herd mates.

Activity Recording

Animals were equipped with electronic activity tags fitted on neckbands (Alpro, version 6.60; DeLaval, 2007). Activity data, measuring physical impulses from changes in acceleration by head and neck movements as counts per hour, for each cow were transferred from the activity tags into the AlproWin management system every hour via wireless stations in the housing facility. Faulty tags were replaced and data from any affected period were omitted from further analysis. During the study period (7.5 yr, with more than 200 tags in use at any time), 53 tags were replaced. The majority of tags stayed permanently on the animals throughout their lifetime at DCRC. To stabilize variation in the hourly activity counts, data were ln-transformed before being processed in the estrus detection algorithm described below.

Algorithm Steps for Detection and Description of Estrus Activity

To detect the episode of high activity and the duration and strength of the activity bouts, progressive steps were undertaken in the analysis. First, the algorithm used exponential smoothing to establish an hour-by-hour reference value. Then, the detection of the episode and its duration and strength were based on smoothed deviations from the reference.

Step 1: Hourly Reference Value. Activity data were hourly activity count records. It was assumed that each animal would have an individual diurnal rhythm. An exponential smoother was applied to establish a smoothed hourly activity ($\bar{y}_{h,d}$) using activity counts from previous days [equation 1]:

$$\bar{y}_{h,d} = (1-\alpha)\bar{y}_{h,d-1} + \alpha y_{h,d-1}. \quad [1]$$

The smoothing factor α gives the relative weight of new information. The smoothed value is based only on information available up to the previous day.

Step 2: Deviations from Reference Value. For each hour, the deviation between the observed activity and the reference was calculated as a simple difference, still in ln units:

$$x_{h,d} = y_{h,d} - \bar{y}_{h,d}. \quad [2]$$

Step 3: Smoothed Deviations. The deviations [equation 2] were recorded over short time intervals (1 h) and were therefore highly variable. An exponential smoother similar to equation 1 with smoothing factor β was applied to recover the systematic part of the deviations [equation 3]:

$$\bar{x}_{h,d} = (1-\beta)\bar{x}_{h-1,d} + \beta x_{h,d}. \quad [3]$$

Step 4: Detection of High-Activity Episodes. The smoothed deviations were expected to be (almost) free of diurnal variation. Therefore, deviations exceeding a set threshold (**δ**) indicated a systematic change. A rule was applied requiring 3 consecutive deviations to exceed the threshold to indicate the initiation of an episode. The high-activity episode ended when 3 consecutive deviations were below the threshold.

Step 5: Description of Activity Episodes. The time points when each episode started and ended were noted. The duration in hours was measured from when the episode started until it ended. The strength of each episode was calculated as the mean of the 3 highest deviation values during the episode. Each episode was numbered within parity. The interval between consecutive episodes, in fractions of days, was used as a measure of regularity. Episode duration in hours and regularity were ln-transformed before ANOVA. From this step, episode characteristics were subjected to further analysis as repeated records from the same animal using the first 5 or fewer episodes.

Step 6: Reset Rules. At any new parity, the algorithm was reset. A reset was also performed following replacement of faulty tags. The reset involved priming the smoothed reference values to the mean values for the herd. Following the end of an episode, a new episode could be initiated only after 3 consecutive smoothed deviation values had been below zero. This rule was developed to protect against multiple episodes at short intervals.

Algorithm Optimization. A subset of the data (learning data) was used to find appropriate thresholds and settings for the episode detection algorithm. This consisted of 461 records of successful AI that either gave a calf or resulted in a confirmed pregnancy. Hourly activity data were selected from 14 d before to 14 d after successful AI. This period was divided into 3 periods: a pre-AI period (−14 to −2 d), an AI period (−1 and 0 d), and a post-AI period (1 to 14 d). The criteria for selection of settings were 1) the largest number of episodes in the AI period (i.e., true positives), calculated as the detection rate, and 2) the smallest number of episodes outside the AI period (i.e., false positives), calculated as the daily error rate. Because these 2 measures were antagonistic to each other, a compromise was needed. Consequently, a search of optimal settings was performed. For further calculations in the complete data set, smoothing with α = 0.25, β = 0.25, and δ = 0.70 was applied. This was equivalent to doubling the activity measured in linear counts per hour.

Algorithm Validation

Diurnal changes in activity counts per hour and smoothed values were investigated using a linear mixed model. Random individual variance in the diurnal profile was included in the model

$$y = \mathbf{Xa} + \mathbf{Zb} + \mathbf{Ie},$$

where variation in the trait variables y (ln-transformed activity per hour and smoothed deviations) was modeled as dependent on systematic effects **a** given in the design matrix **X**, including general diurnal profile (hour of day, 24 levels), age group (heifer, cow), parity of cows (1, 2, 3, 4), interaction between profile and age group, and the interaction between profile and parity of cows. Random effects of individual profiles within age group and parity were in **b** with incidence matrix **Z**. This was used as an error term in testing effect interactions between profiles and age group or parity. Random residuals in **e** were assumed to be normally distributed with incidence given by the identity matrix **I**. Estimates of fixed and random effects were obtained using the HPMIXED procedure of SAS (version 9.2, SAS Institute Inc., Cary, NC).

To test the agreement of the activity traits with the known measure of estrus based on milk progesterone, a concordance test was carried out. Similarly, concordance was calculated between activity traits and visual observations of estrus signs, including performed AI. Correlations between days from calving to first episode of high activity and a similar trait based on milk progesterone were computed using records from cows that had both traits recorded. To avoid unwanted influence from infrequently sampled data, animal-parities were qualified for the analysis if records of at least 90 d that included both types of information were available starting from 5 DIM.

Records Based on Milk Progesterone. A subset of the cows had milk progesterone determined at least 2 times per week to assign reproductive status to each day after calving using a combined biometric and biological model (Friggens and Chagunda, 2005). To reduce random noise in the time series, the progesterone values were smoothed using an extended Kalman filter, which used a local linear growth model with outliers (e.g., Smith and West, 1983). The smoothed values were posterior mean estimates of the true level at time t given all of the time series available to time t. The assumptions made in the local linear growth model, estimation of parameters, and implementation of the extended Kalman filter are described in Korsgaard and Løvendahl (2002). Days to first estrus was estimated as the day when the smoothed progesterone level decreased below 4 ng/mL following a peak during which this threshold had been exceeded. The 4 ng/mL limit was chosen because smoothed levels responded slower than raw levels, as had been used in other studies. Therefore, the estimate of days to first estrus was longer than the standard of other studies, which measured the days to first increase above 3 ng/mL. Data on progesterone levels were available for 376 of the cow-lactations having activity data.

Concordance between activity and progesterone-detected cyclic status was estimated using cow-lactations having both measures. Each day after calving until milk progesterone exceeded 4 ng/mL in 2 measurements was assigned as anestrous, and days thereafter as cyclic. Similarly, days before first episode of high activity were anestrous by activity and thereafter cyclic by activity. Thus, days after calving could fall into 4 categories: 1) anestrous by both activity and progesterone, 2) cyclic by activity and anestrous by progesterone, 3) cyclic by progesterone and anestrous by activity, or 4) cyclic by both activity and progesterone. Concordance was calculated as the fraction of days assigned to the same category by both methods. Another measure of concordance was the fraction of high-activity episodes during days assigned as cyclic by progesterone out of the total number of episodes. Measures of concordance were studied as functions of the detection threshold δ.

Concordance with visually observed estrus signs was calculated from high-activity episodes coinciding with positive visual observations of estrus within a time frame of 4 d. Visual observations of estrus were categorized as positive if at least 1 of the visual criteria were positive or if AI was performed. Concordance with visual estrus signs was also calculated for progesterone-based estrus as a reference. Furthermore, the correlation between days to first estrus detected by either method was estimated.

Records with BCS. Body condition score was used as an indicator of body fat content. Fortnightly BCS using the tailhead system on a 1 to 5 scale with 0.25-unit divisions were used for lactating cows (Mulvanny, 1977). Mean of scores for each of the first 5 mo after calving for each cow-lactation were used as indicators of body fatness during the observed part of lactation.

Sources of Variation in the Estrus Behavior Traits. A single-trait mixed model was used to determine the effects of systematic factors on the activity traits in an ANOVA. Random individual animal and year-season effects were included in the model

$$\mathrm{y} = \mathbf{Xa} + \mathbf{Zb} + \mathbf{Ws} + \mathbf{Ie},$$

where variation in the trait variables y (DFHA and duration, strength, and regularity of activity) was modeled as dependent on systematic effects **a** given in the design matrix **X** including breed (Red Dane, Holstein, Jersey), age group (heifer, cow), parity (0, 1, 2, 3, 4), breed by age group interaction, episode number (1, 2, 3, 4, 5), and interaction of age group by episode. Random effects of animals across and within parities were in **b** with incidence matrix **Z**. Random effects of year-months (used as short seasons) were in **s** with incidence matrix **W**, and random residuals in **e** were assumed to be normally distributed with incidence given by the identity matrix **I**. Estimates of fixed effects and significance of random variance were obtained using the

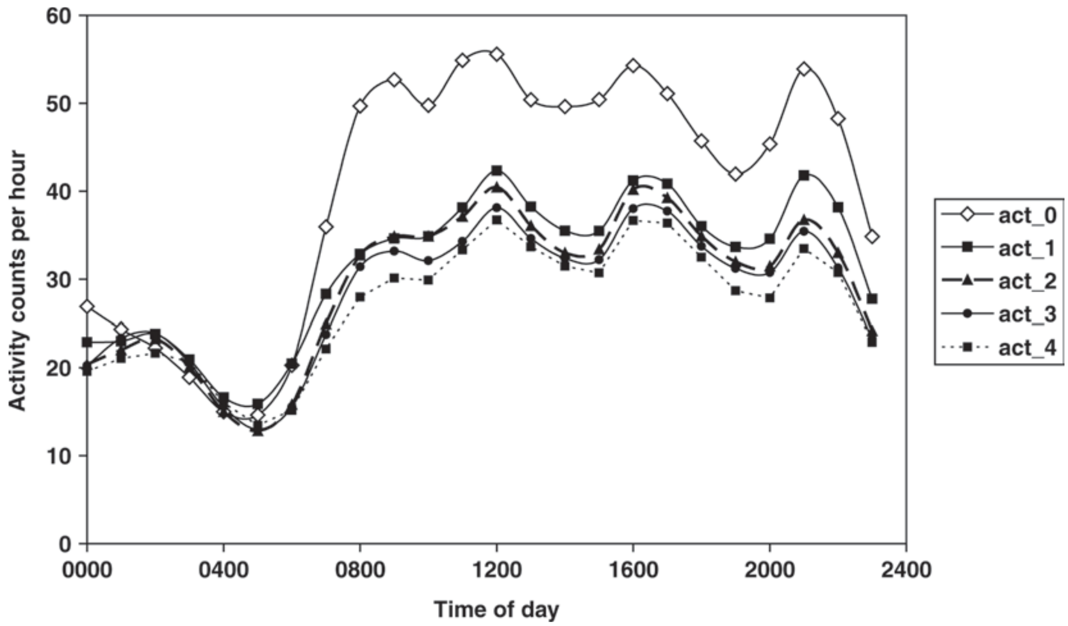

Figure 1. Physical activity distribution over 24 h in dairy heifers (age 12–18 mo) and cows in the first half (5–155 DIM) of their lactation. Activity is shown as measured activity counts per hour using the DeLaval (Tumba, Sweden) activity tags. Results are simple group means for heifers (act_0) and cows in parities 1 to 4 (act_1 to act_4).

MIXED procedure of SAS (version 9.1, SAS Institute Inc.).

A linear fixed multivariate model was used to estimate correlations between BCS and activity traits:

$$y = \mathbf{Xa} + \mathbf{Ie},$$

where trait variables y included monthly mean BCS values, DFHA, and episode strength and duration, **a** was the fixed effect vector with parity and breed and their interaction with incidence matrix **X**, and **e** was the random error with incidence given by the identity matrix **I**.

RESULTS

Diurnal Activity Profiles of Heifers and Cows

On a daily basis, physical activity of maiden heifers and cows of any parity increased from approximately 0600 h toward a high level at approximately 0800 h. From then on, high activity continued until approximately 1700 h. Between 1700 and 2000 h, activity was generally low. There was a surge in activity to about 40 physical activity counts per hour at approximately 2100 h, after which activity decreased to a nighttime low level, which was stable between midnight and 0600 h (Figure 1). Maiden heifers had the highest activity levels followed by cows in first and then later parities. All age-lactation classes largely followed a common time profile (Figure 1), although the heifers had a profile differing from that of cows ($P < 0.001$). Individual-level variance in diurnal profiles was significant, although with a low repeatability ($t = 0.22$, Z-test; $P < 0.001$).

Algorithm Development

Efficiency of the Heat Detection Algorithm. The diurnal changes in activity measures were effectively handled by the algorithm, both overall and for interactions with age-parity (data not shown). Furthermore, individual-level variance was no longer detectable for the smoothed deviations (data not shown). Detection rates and daily error rates based on activity measurements using different threshold levels for cows that had successful AI are presented in Table 1. The results indicated a tradeoff between detection rate and error in favor of high detection rate at the cost of increasing error rate. Detection rates and daily error rates were almost similar for different levels of the smoothing factors α and β, between 0.30 and 0.15 (not shown), but with the best results obtained at 0.25 for both smoothers. The combination of smoothing at α and $\beta = 0.25$ and using $\delta = 0.70$ gave 74.6% detection rate and 1.3% daily error rate and hence was chosen for use in further steps for the entire study (Table 1). The activity episodes were significantly ($P < 0.001$) longer during AI-estrus than either before or after AI-estrus (mean duration

= 10.33, 5.38, and 6.23 h for during, before, and after estrus, respectively; Table 1). Strength of activity in episodes was also higher during estrus (1.27 deviation units) than before and after estrus (0.77 and 0.85 units, respectively). During estrus, activity was significantly more regular (24.2) than before (19.61) and after the estrus episode (15.56; $P < 0.001$).

Algorithm Application. The characteristics of activity episode traits for all data, including the period from DIM 5 to 155 for all cows and heifers, resembled that of activity episodes detected from the learning data set during the AI period. In general, an activity episode lasted 9.24 h in heifers and 8.12 h in cows, with the average strength of 1.03 ln-units in both age groups. Holsteins were of similar age as Jersey and Red Dane heifers at DFHA (age = 418–420 d). Across parities, Red Dane cows had the smallest number of DFHA compared with Jersey and Holstein cows (36 d vs. 41 d; $P < 0.01$).

Concordance Between Activity Measures and Progesterone. The relationships between activity traits and progesterone measures are presented in Table 2. In general, there were numerically fewer estrus episodes detected by progesterone than periods of high activity. This was true with all the delta-threshold levels apart from 0.90. Similarly, there were fewer cases when cows were identified as cyclic by activity tags but anestrous by progesterone measurements than there were cases when cows were identified as cyclic by progesterone and anestrous by activity tags. With threshold values lower than 0.90, days to first estrus determined by activity were shorter than those determined by progesterone. The days from calving to DFHA correlated nonsignificantly with the similar trait based on milk progesterone (r = 0.09, NS; Table 2). Perfect concordance was observed in only 55 of 332 cases. A further 49 cases were detected by activity 3 wk before progesterone estrus, another 18 cases detected 6 wk before, and 19 cases detected 3 wk later than by progesterone. This gave a total of 141 out of 332 cases, resulting in 42% of the cases being in some kind of concordance (Figure 2).

Concordance with Visually Scored Estrus Signs. Progesterone-detected estrus was supported by positive visual signs in 60% of the cases (Table 3). The comparable fraction was 55% for activity at the threshold set to 0.90 and lower for the following lower settings (Table 3). At $\delta = 0.70$ the total number of high-activity episodes and visual signs was almost similar to the total number obtained using progesterone, but with fewer (47%) being in agreement.

Systematic and Random Factors Affecting High-Activity Episode Characteristics. The effects of systematic and random factors on activity traits are presented in Table 4. Breed had a highly significant effect ($P < 0.001$) on duration and strength of the activity episode in the multiple episodes. Age group significantly affected ($P < 0.001$) the regularity of episodes. Parity within age group also significantly affected regularity of the episodes ($P < 0.01$). The random effect of cow affected DFHA and episode strength ($P < 0.001$) as well as duration ($P < 0.01$). Red Danes had significantly fewer days to first estrus than Holsteins and Jerseys. However, Jerseys had significantly shorter duration and less strength than both Red Danes and Holsteins of comparable age. The intensity of estrus behavior was strongest in Red Danes. When all episodes were considered, heifers had shorter intervals between episodes (regularity) than older cows. Age effects were therefore mostly relevant when heifers were evaluated along with lactating cows.

Relationships Between Episode Characteristics and BCS. In the first 5 mo after calving, BSC had negative correlation to DFHA (r = −0.08, −0.11, −0.12, −0.12, and −0.14, respectively, in each of the first 5 mo after calving; $P < 0.01$). These results indicated that low BCS in early lactation predispose to later onset of first episode of high activity. In mo 3 and 4 after calving, correlations of activity episode strength to BSC were positive but low (r = 0.08; $P < 0.05$). Residual correlations from multivariate analysis (which included breed and parity) also showed negative correlations between days to first activity episode and BCS over the first months after calving (data not shown).

DISCUSSION

Detection and Characterization of Activity and Estrus

Assessment of physical activity of cows using pedometers and activity tags has evolved since it was first described (Farris, 1954) through the advent of advanced electronic activity tags that deliver data by wireless connections (Firk et al., 2002). The primary purpose of using the meters has been to detect onset of estrus and aid timing of inseminations (Maatje et al., 1997; Roelofs et al., 2005b). With advanced activity tags, reading of activity has increased in frequency from twice daily to 12 or 24 times per day, as in the present study. However, for detection and characterization of estrus behavior, the diurnal variation in frequently recorded activity needs to be accounted for in the detection algorithms. The current study has shown that diurnal variation in activity mostly follows a common profile, but also that the profile changes in level with age and lactation number. Furthermore, individual animal variation is present as a diurnal profile. However, an unknown

Table 1. Dependency between threshold setting (δ) and rates of detection and false positive error rates based on activity measurements in 461 animal-parities with AI giving confirmed pregnancies

Threshold (δ)	Total episodes (n)	Animals with episodes (n)	Detected high-activity episodes (n)[1]			Detection rate[2] (%)	Error rate[3] (%)	Duration of estrus (h)			Strength of estrus (ln units)		
			Early	On time	Late			Early	On time	Late	Early	On time	Late
0.90	308	294	20	260	27	56.4	0.38	6.35	9.10	7.89	1.13	1.39	1.13
0.85	340	313	25	278	36	60.3	0.49	6.48	9.41	7.06	1.07	1.36	1.06
0.80	398	348	36	311	48	67.5	0.67	6.22	9.56	6.83	0.97	1.32	1.00
0.75	453	373	56	328	60	71.2	0.93	5.64	10.00	6.63	0.86	1.30	0.94
0.70	531	392	82	344	84	74.6	1.33	5.38	10.33	6.23	0.77	1.27	0.85
0.65	626	415	105	366	106	79.4	1.70	5.55	10.52	6.54	0.73	1.22	0.83
0.60	757	432	139	383	142	83.1	2.26	5.59	10.81	6.50	0.68	1.20	0.75
0.55	925	442	181	389	190	84.4	2.98	5.73	11.54	6.38	0.63	1.19	0.69
0.50	1,172	449	242	388	237	84.2	3.85	5.58	11.90	6.53	0.57	1.16	0.64

[1]Early = period from 14 to 2 d before AI; on time = day before and day of AI; late = period from 1to 14 d after AI.

[2]Detection rate is the percentage detected on time of the 461 possible animals.

[3]The error rate is a daily error rate calculated as the number of early plus late divided by 13 d early plus 14 d late, seen as percentage of the 461 possible animals.

Table 2. Concordance measures between estrus activity traits and progesterone-determined traits for 376 cow lactations that included both types of data[1]

Concordance measure	Threshold (δ)						
	0.90	0.85	0.80	0.75	0.70	0.65	0.60
Periods of high activity							
Total high-activity episodes (n)	738	855	1,018	1,217	1,463	1,845	2,351
Episodes detected when anestrous by progesterone (n)	83	92	117	141	167	205	258
Episodes detected when cyclic by progesterone (n)	655	763	901	1,076	1,296	1,640	2,093
Days during lactation with assigned status							
Total lactation days with assigned status (n)	52,526	52,526	52,526	52,527	52,527	52,528	52,531
Days defined as anestrous by both activity and progesterone (n)	5,663	5,514	5,199	4,924	4,631	4,190	3,710
Cyclic by activity, anestrous by progesterone (n)	1,345	1,494	1,809	2,084	2,377	2,818	3,299
Cyclic by progesterone, anestrous by activity (n)	14,424	12,208	10,328	8,422	6,491	4,977	3,492
Cyclic by both progesterone and activity (n)	31,094	33,310	35,190	37,097	39,028	40,543	42,030
Fractional agreement	0.70	0.74	0.77	0.80	0.83	0.85	0.87
Days to first estrus or episode of high activity							
Days to first estrus, progesterone	44.2 (1.2)	44.5 (1.2)	44.4 (1.2)	44.4 (1.2)	44.6 (1.2)	44.5 (1.2)	44.3 (1.2)
Days to first high-activity episode	45.1 (1.6)	42.4 (1.4)	41.1 (1.4)	38.7 (1.3)	37.1 (1.3)	32.8 (1.1)	28.5 (1.0)
Pearson correlation	0.16**	0.17**	0.12*	0.08	0.09	0.10	0.12*

[1]Estrus was detected by progesterone in 863 cases. Results are means (SEM).

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

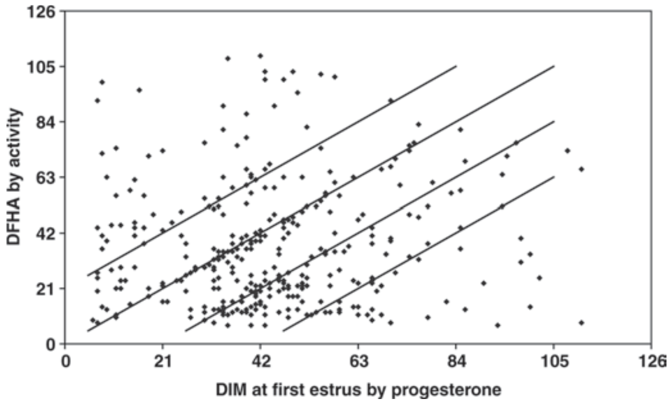

Figure 2. Concordance between days to first estrus determined from milk progesterone and days to first episode of high activity (DFHA). Lines indicate concordance with no displacement and with 3- and 6-wk displacements. Threshold for activity episode detection was set at 0.70 units.

part of the individual-level component could arise from activity tags that are less well calibrated. In the current study, estrus was indicated when the actual activity exceeded that of an exponentially smoothed mean for the same hour by a given threshold value. By taking deviations from the smoothed means for every hour, diurnal variation was effectively adjusted for. Similar approaches were used by others (At-Taras and Spahr, 2001; Roelofs et al., 2005b) using moving averages. Having obtained deviations and further smoothed the data, they were taken through a logical filter to protect against false positives. The filter reduces the false positives and also tends to remove atypical and very short activity episodes. Such episodes are frequently observed in multiple ovulations and in cows with either low BCS or very high yield (Lopez et al., 2005). Thus, optimal filter settings depend on whether the focus is detection of normal estrus episodes or both the normal and the atypical episodes. The current study applied a simple detection method. More advanced methods employing such methods as Kalman filters and fuzzy logic (e.g., De Mol and Woldt, 2001) have been described elsewhere. The method applied in the current study detected and characterized activity traits with detection and error rates comparable to previously reported methods based solely on activity meter readings (e.g., At-Taras and Spahr, 2001; Roelofs et al. 2005b).

The current study recorded activity in 1-h periods. This enabled the estimation of duration of activity periods. Activity episodes lasted 10.33 h when recorded around AI. This was longer in heifers (9.24 h) than in cows (8.12 h) for the complete data. In comparable housing systems, the duration of estrus was similar. For example, Roelofs et al. (2005a) reported estrus duration of 11.8 h when recorded by visual observation at 3-h intervals, and 10.0 h when recorded by pedometers in 2-h intervals. Even shorter duration of estrus was found when standing estrus recorded by visual observation was used (Yoshida and Nakao, 2005). In another study, the duration of standing estrus recorded by an electronic device was 9.9 h in cows with normal single ovulations but decreased to 4.3 h in cows with multiple ovulations (Lopez et al., 2005). The existence of a negative phenotypic relationship between estrus duration and yield as well as BCS (Lopez-Gatius et al., 2005) may explain the differences between the results of the studies. The ability to determine duration of estrus using electronic devices allows for more in-depth studies and studies with larger cohorts of dairy cattle, as required for genetic studies (Løvendahl and Chagunda, 2009).

The intensity or strength of estrus was determined as a deviation from a moving average of the individual cows in logarithmic units and thereby as an indicator of relative increase in activity. These units are not fully comparable across studies, first because units of measure are defined by the manufacturers, and second because devices are either attached to a neckband or attached around the leg (Maatje et al., 1997). In the current study, neck activity measurements were used. From these measures it was found that the relative increase

Table 3. Concordance measures (shown in number of cases out of 376 cow lactations) between estrus activity traits and visual estrus at different threshold levels

Threshold (δ)	Visual estrus only	Activity only	Both visual and activity	Total number	Fraction of concordance[1]
0.90	64	201	248	513	0.55
0.85	50	228	267	545	0.54
0.80	36	261	289	586	0.53
0.75	30	310	304	644	0.50
0.70	22	374	334	730	0.47
0.65	17	439	354	810	0.45
0.60	12	521	384	917	0.42

[1]Fraction of concordance is calculated as number detected by "both visual and activity" divided by the sum of "activity only" plus "both visual and activity."

was the most effective in detection of onset of estrus episodes. This was achieved by transforming activity to ln units. As a result, a general threshold rule could be applied across parities, breeds, and individual animals. A relative increase was also used as the indicator in other studies (At-Taras and Spahr, 2001; Roelofs et al., 2005a). Although the intensity in measured units may provide further information, it requires proper calibration of the devices. Intensity may also be determined as number of mounts when heat mount detectors are used [e.g., HeatWatch (CowChips LLC) as used by Lopez et al., 2005].

The number of days to first estrus after calving is an accepted indicator of dairy cow fertility and can be accurately determined from frequent milk progesterone measurements (e.g., Bulman and Lamming, 1978; Friggens and Chagunda, 2005). In the current study, concordance between progesterone-based detection of days to first estrus and DFHA was not perfect for all records. Using progesterone as the gold standard, activity tended to give several false positives and was not able to pick up all estrus episodes. However, clear indications were obtained that for several cows the 2 measures were in useful agreement. The not-so-perfect concordance may be caused by some cows having silent behavioral estrus and others having pseudo estrus, or activity not being completely determined by estrus. For instance, a large proportion of first ovulations may occur without external heat signs. The basis of this may be that some animals show estrus behavior before they have their first period of elevated progesterone and vice versa. This may be valid if the behavior is not determined completely by progesterone but by a cascade and interaction of progesterone and other hormones. This implies that the 2 traits, activity and progesterone measurements, may not be exactly the same. Because both traits are involved in expression of estrus, there may be an advantage in combining the information (O'Connell et al., accepted). Also, to establish the real difference or similarity between these 2 traits, larger studies with more information from different sources of measuring estrus are needed. The concordance between progesterone and activity was confirmed by visual signs of estrus. However, this study was not planned for comparisons between visual detection of estrus and activity as indicator. In practice, activity information was available to observers; hence, observers were not unbiased in their selection of cows for inspection. As such, in the current study visual signs were used only to support the progesterone-based measures.

Effects of Breed, Parity, and Episode Number

Red Dane cows had their first estrus episode earlier than Jersey and Holstein cows. However, parity did not affect DFHA. In a comparative study, Brown Swiss and Jerseys had shorter calving intervals than Holsteins (Garcia-Peniche et al., 2005). Because breeds differ in BCS and yield (Friggens et al., 2007), the differences between breeds in days to first estrus could be attributed to differences in yield and in BCS. This was supported by the negative correlations between BCS and DFHA and the weak correlations of residuals. Results in the current study are in agreement with previously reported negative relationships between fertility, BCS, and yield, both at the genetic and phenotypic level (Veerkamp et al., 2000; Wassmuth et al., 2000; Pryce et al., 2002; Royal et al., 2002). Weak but unfavorable correlations

Table 4. Main effects of breed, age group, and parity on estrus activity episode traits[1]

Factor level	DFHA[2,3] LSM ± SE (episode 1)	DFHA GM	Duration[3] (h) LSM ± SE (all episodes)	Duration GM	Strength (ln units) LSM ± SE (all episodes)	Strength FOI	Regularity[3] (d) LSM ± SE (episodes 2+)	Regularity GM
Breed								
Red Dane	$3.381^a \pm 0.048$	29.4	$1.992^a \pm 0.026$	7.3	$1.055^a \pm 0.018$	2.87	2.559 ± 0.048	12.9
Holstein	$3.499^b \pm 0.046$	33.1	$1.967^a \pm 0.024$	7.2	$1.029^a \pm 0.017$	2.80	2.635 ± 0.046	13.9
Jersey	$3.524^b \pm 0.054$	33.9	$1.837^b \pm 0.032$	6.3	$0.951^b \pm 0.022$	2.59	2.682 ± 0.060	14.6
Parity								
Heifer			1.955 ± 0.028	7.1	1.013 ± 0.019	2.75	$2.395^a \pm 0.054$	11.0
First parity	3.469 ± 0.038	32.1	1.909 ± 0.020	6.7	1.000 ± 0.013	2.72	$2.906^b \pm 0.040$	18.3
Second parity	3.428 ± 0.042	30.8	1.934 ± 0.021	6.9	1.037 ± 0.014	2.82	$2.772^b \pm 0.041$	16.0
Third parity	3.433 ± 0.054	31.0	1.908 ± 0.027	6.7	1.018 ± 0.018	2.77	$2.765^b \pm 0.052$	15.9
Fourth parity	3.543 ± 0.091	34.6	1.888 ± 0.047	6.6	0.986 ± 0.032	2.68	$2.976^b \pm 0.090$	19.6

[a,b]Superscripts within factors denote significant difference within a trait ($P < 0.001$).

[1]Results are least squares means (LSM ± SE) with corresponding geometric means (GM) or folds of increase (FOI). High-activity episodes were detected using the threshold set at $\delta = 0.70$.

[2]DFHA = days to first episode of high activity.

[3]Results (LSM ± SE) are in ln units, with corresponding geometric means (GM) in measured units.

were also detected between BCS and estrus duration and strength, thus giving support, at the phenotypic level, to previous findings of general negative associations between fertility traits and BCS (e.g., Pryce et al., 2000; Royal et al., 2002).

CONCLUSIONS

The results of the present study have shown that the method for determining DFHA and duration, strength, and regularity of estrus based on electronic activity tags may be of value in finding cows in estrus, and this could be helpful in recording associated fertility traits. Important information on intensity and duration of estrus can be acquired. These are all part of the complex of traits describing fertility and may as such have a role in genetic selection for improved fertility (Løvendahl and Chagunda, 2009). Unfavorable consequences of selection for increased milk yield have been reported to affect fertility of dairy cows with longer calving intervals, a result of later onset of estrus and of decreased fecundity at AI (Veerkamp et al. 2000; Pryce et al., 2002; Philipsson and Lindhe, 2003; Weigel, 2006). Strategies using milk progesterone measurement could be employed alone or in combination with activity measurements. Both methods can provide information without involving farmer observations, judgments, or management decisions such as deliberately delayed inseminations in high yielding cows.

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