

The evolution of sensor-based technologies in dairy production

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Abstract

Sensor-based management is growing rapidly in dairy farming. Activity, behavior and rumination monitors and data from automated milking systems and calf feeders are established management tools and hold promise for earlier or more efficient detection of health problems. However, gaps remain in validation and especially in turning streams of data into actionable information. On average, dairy herds can achieve comparable reproductive performance with management emphasizing estrus detection by activity monitors or timed insemination programs, but herd-specific variables will affect relative performance. Sensor-based screening of fresh cows may be useful to save labor or reduce disruptions to cows' routines, but more validation is needed before this can augment or offset skilled, rational detection of health problems.

Key words: activity, automation, health, reproduction

Promise and limitations of using sensors to manage cows

There is a growing number of sensors available as aids for dairy cattle management. The best-established technology is automated activity monitors, mostly based on accelerometers. Activity sensors establish a cow-specific rolling baseline of approximately one week of data, typically in 2-hour increments and calculate current deviation from that that value. Some systems at least potentially also attempt to correct for herd-level changes. Generally, the appeal of sensors relates to reduction of the need for labor (especially skilled labor), 24/7 observation, consistency of function, and possibly earlier or more accurate detection of actionable items. Any of these can be negated when the sensor or its software fails.

Often, sensor software displays a wide array of cow-level measures, commonly in a graphical format. Many interfaces are focused on individual cows, which may work in small herds but are less useful in large herds. There is considerable variation in the ability of sensor software to communicate with parlor or other herd management software; most do not use data other than what is in the sensor system itself. Moreover, many lack useful metrics for analysis of herd-level performance over time. This shortcoming requires more attention from system providers to share and integrate data and to allow meaningful herd-level analysis.

There is a small but increasing body of literature that provides independent, scientific evaluation of sensor function and the performance of management using sensor systems versus conventional management. Producers are likely best served by insisting on having such evidence before considering purchase of systems.

Particularly for application in detection of health problems, it is important to have clear goals for the sensor systems. They should provide more objective, accurate, or consistent data more quickly or inexpensively than alternatives. The cost of

hands-on screening may be measured in both paid labor and disruption to cows' key functions of eating, drinking, and lying down. It is probably unrealistic to expect sensor-based systems to provide an actionable working diagnosis. Rather, they may reduce the labor required for repetitive, low-predictive value mass screening of fresh cows. Ideally, these systems would integrate with other data streams such as milk yield, parity, calving history and other recent disease events, screening to identify a meaningfully reduced selection of cows for skilled assessment by people for action. These technologies should reduce the total demand for person-hours for disease detection while maintaining or improving the efficiency and accuracy of taking beneficial actions. Therefore, the goal is to augment the efficacy of health management rather than simply to eliminate the need for human resources.

Management of reproduction

Wearable activity monitors are well established tools for detection of estrus in dairy cows. The principle is that in proestrus and estrus, cows' walking activity and restlessness increases 2 to 5-fold or 2 to > 3.5 standard deviations above their individual rolling mean for the previous 7 to 10 days. This spike in activity lasts approximately 6 to 24 hours. The increase in activity generally precedes the onset of standing estrus by several hours. Ovulation occurs 26 to 30 hours after the increase in activity above typical software thresholds to signal estrus.^{1,2,3,4} Although the timing of ovulation and therefore of insemination may be more precise relative to the peak of activity, alerts are based on the onset of increased activity. In one study, 88% of cows detected in estrus by activity had ovulated by 48 hours after onset of estrus.⁵ It is practically difficult to manage based on peaks, so breeding is based on the alert of onset.

Several reviews have summarized the performance of activity monitors for detection of estrus. The reference test method (visual observation, serial measurement of progesterone in blood or milk, or repeated ultrasound scans) and outcome (behavioral estrus or ovulation) matter to the relative performance of activity monitors. No single test for estrus is perfect. For housed cows, the sensitivity of activity monitors for estrus detection is typically 60 to 80%.^{1,6} That aligns with controlled field studies^{7,8,9,10,11} in which approximately 70% of cows are detected in estrus between 50 and 80 DIM. Among other considerations, that should be compared with herd-specific compliance in administering synchronization protocols for timed AI. Moreover, this underlines that management of reproduction primarily with activity monitors requires a complementary intervention protocol with timed AI as a backstop for the ~ 30% of cows not detected in estrus by approximately 70 DIM and for open cows at pregnancy diagnosis.

Generally, more intense expression of estrus based on activity is favorable for fertility. Intensity includes the amplitude (height of the peak above baseline) and duration (how many hours above the estrus alert threshold). Greater peak activity

appears to be especially important, with cows with ≥ 3 -fold increase having greater probability of pregnancy per artificial insemination (P/AI) than those triggering an estrus alert with a lower relative increase in activity.¹² Similarly, data from 8 large herds in Germany showed a positive correlation between peak and duration of increased activity in cows signaled in estrus, but only the peak (activity index > 90 on an arbitrary scale of 0 to 100, where estrus is > 35) was associated with 40% relatively greater P/AI, albeit from a low baseline.¹³ Similarly, in a study with cows wearing 2 sensors, considered separately, cows with an activity index > 80 , > 3.3 -fold increase, or > 12 -hour duration of increased activity had 10 percentage point greater P/AI (from ~ 32 to 42%).⁴

Several controlled field studies are consistent in showing that management for first insemination based primarily on automated activity monitoring (AAM) versus timed AI (TAI) result, on average, in similar proportions of cows pregnant by end of the treatment period (75 to 85 DIM)^{4,7,9} and through the whole lactation.^{4,7,10,14,15,16} There are several important considerations that emerge from these studies:

- While performance was consistently comparable between AAM and TAI within studies, there were differences among herds in the relative performance of one management system or the other.^{4,9,14} Success of programs based on activity or TAI will depend, among other variables, on compliance with synchronization protocols, the prevalence of anovular or lame cows, stocking density and floor type, function of the activity system, and the frequency of AI (and consequently the precision of timing of AI relative to estrus and ovulation). Therefore, selection of reproductive management tools should be herd-specific.
- To assess performance, it is important to focus on pregnancy rate and the proportion of cows pregnant within an economically optimal range i.e., 80 to 120 DIM, not on P/AI, e.g. Rial et al. (2022).¹⁰ Activity-based programs for first AI may have lesser P/AI but allow for 2 inseminations by 80 DIM in many cows vs. one in a fully timed AI program.^{9,16} As for the cost of hormones for synchronization,¹⁷ the cost of an additional breeding with activity is minor relative to the benefit of pregnancy within the optimal timeframe. In any case, it is essential that AAM be complemented with a TAI protocol for the 20 to 30 % of cows not detected in estrus by ~ 70 DIM and for cows open at pregnancy diagnosis.

In a modeling study,¹⁸ given the assumptions, AAM was always more profitable than management based on visual estrus detection. However, whether AAM was more or less profitable than 100% TAI or 75% AAM/25% TAI depended on AAM system overhead (\$5,000 or \$10,000), cost per tag (\$50 or \$100), and estrus detection rate (60 or 80%). In a controlled trial of TAI vs. AAM complemented by TAI,⁷ the proportion of cows pregnant by 75 DIM and pregnancy rate to 300 DIM, as well as the economic return were similar for the two management programs. Economic modelling using data from a field study in primiparous cows that considered the interaction of genomic reproduction index and management based on AAM or TAI¹⁸ concluded that neither management program was consistently superior beyond the margin of error of the model.

Timing of insemination based on AAM alerts follows the same principle as any AI, relative to the LH surge at the start of standing estrus and ovulation ~ 30 hours later. For AAM, that means approximately 6 to 16 hours after the onset of estrus based on increased activity,^{2,20} or soon after peak activity. We conducted

an observational study on the time of AI relative to estrus alerts in 4 herds.⁸ For multiparous cows, there was no difference in P/AI among alert-to-AI intervals of 0 to 8, 8 to 16, or 16 to 24 hours, although all were low (all services P/AI $\sim 31\%$). In primiparous cows, earlier AI was much better: P/AI was 49% at 0 to 8 hours, 36% at 8 to 16 hours, and 32% between 16 and 24 hours. Using a single AAM system, Stevenson (2014)² also found a difference between parity groups, but P/AI was optimal at 0 to 12 hours in multiparous cows and at 13 to 16 hours in primiparous cows. Practically, optimal performance is likely achieved if the alerts are acted upon morning and afternoon, essentially following the traditional “am-pm rule”, but the magnitude of the benefit of conducting AI twice vs. once per day may be smaller than the effect of other variables on P/AI. Conversely, more precise timing of AI could achieve a meaningful increase in P/AI if AAM system function and settings and AI technique are already optimized. There are a few studies that suggest some benefit when using sexed semen with AAM of AI at ~ 20 to 28 hours after the estrus alert in Jersey cows,³ Holstein heifers,²¹ or synchronized Holstein heifers,²² particularly in the latter study if AI was done within 1 hour of twice-daily checks of estrus alerts (as opposed to following the “am-pm rule”).

In a previous study with pre-breeding monitoring only from 35 DIM,⁸ 83% of cows were detected in estrus by AAM alone between 55 and 80 DIM. Purulent vaginal discharge (PVD) at week 5, being lame and thin (BCS ≤ 2.5) at week 7 or being anovular by week 9 reduced estrus detection to 53 to 68%. A large study in Germany²³ found that cows that experienced stillbirth, RP, metritis or ketosis were less likely to be detected in estrus by AAM. We recently completed a study¹¹ to assess the associations of health-related variables in the transition period with detection of estrus by AAM for first AI and with pregnancy. Overall, 70% of cows were detected in estrus by 75 DIM without intervention. That probability was 7 to 14 percentage points lower in cows that had retained placenta, purulent vaginal discharge (PVD) or endometritis at 35 DIM or were anovular or lost > 0.5 point of BCS by 63 DIM. Cows with elevated serum haptoglobin at 2 DIM or greater blood concentration of BHB at 15 DIM were also less likely to be detected in estrus. Several recent studies^{10,11,15,23} indicate that estrus detected before the end of the VWP (~ 50 DIM), especially > 1 estrus and more intense estrus,²³ is favorable for both detection of estrus by AAM for first AI and success of that breeding. Early estrus detection may be a practical, simple means to summarize a cow’s reproductive status, including recovery from postpartum disorders, and therefore a useful marker of the likelihood of expression of fertile estrus.¹⁰ Conversely, cows with several risk factors against estrus detection could be flagged for prompt intervention for timed AI. There is renewed interest in targeted or individualized reproductive management that incorporates health data from the current lactation, streams of data from sensors, and genotype.²⁴

Aiding health management in fresh cows

With a firm foothold in reproductive management, attention has turned to the potential to use activity and rumination sensors to improve the efficacy, efficiency, or early detection of health disorders. Several studies show clear and substantial differences in retrospective analysis of group mean daily activity, rumination time, milk yield or robotic milking attendance 1 to 2 weeks before clinical detection of mastitis, metritis, ketosis, displaced abomasum (DA), or lameness, relative to healthy cows.^{25,26,27} Therefore, monitoring these indicators with sensors and processing the combined data with validated

algorithms is promising to aid timely and efficient detection of cows with or at high risk of a health disorder. However, these differences are much more difficult to discern for individual cows in real time. There is substantial variation in activity and rumination at the individual animal level.²⁸ In an excellent study^{29,30,31} in one large herd in New York, daily examinations of cows from 1 to 10 DIM with milk yield data but without sensor data was compared to screening using a commercial score that combines activity and rumination time. The sensor-based system provided a generic health alert 0.5 to 3 days earlier than clinical diagnosis of mastitis, metritis, ketosis or DA. Looked at retrospectively, there were substantially lower activity and rumination at least 5 days before diagnosis of ketosis or DA, with sensitivity of the automated alerts of 91 and 98%, respectively. However, the differences were less obvious and the sensitivity for metritis and clinical mastitis were 55 and 58%, i.e., only slightly better than chance. There is also the question of how to act on an alert, even if accurate, in a cow that will have a DA 3 days later but does not at the time.

Another study³² assessed aids for detection of metritis, comparing routine but comprehensive data from herd records (e.g., parity, calving difficulties, and time in the close-up pen), records + BCS change from 3 weeks before to calving, and records + BCS change + sensor-based active, idle, feeding and rumination time to 1 or 2 DIM (i.e., before possible diagnosis of metritis). The sensor data alone to 2 DIM achieved 70% accuracy of prediction of metritis, which increased to 75% with addition of herd record data and no more with addition of BCS data. The study was done in 2 herds. Notably, when the model was optimized for one herd, accuracy was poor when applied to the other, indicating that herd-specific algorithms may be more useful or necessary. The study considered not only predictive value for detection of metritis but also prediction of clinical cure of metritis following antibiotic therapy. Cows that had metritis but cured had behavioral time budgets that differed from healthy cows but much less so than those that did not cure. The latter had substantially less feeding, rumination and active time for days before and up to 3 weeks after diagnosis of metritis. Sensor-based data alone were not superior to herd records alone, but addition of records to behavior data increased the accuracy of prediction of cure of metritis from 77 to 81%; BCS change data increased it to up to 86%. The same research group had previously assessed addition of activity and rumination data to an intensive fresh cow screening program on one large dairy in Florida.³³ They did not detect improvement of outcomes but underlined the need for more studies under a broader set of herd conditions.

Detection of health problems in calves

There has been rapid emergence of group housing of dairy calves with automated milk feeders (AMF). In addition to facilitating greater growth and potentially better health, the detailed data from AMF systems, somewhat analogous to those from milking robots, offer the possibility of earlier, more objective detection of health or management problems. An observational field study of 17 herds with AMF in Ontario, Canada³⁴ identified success and risk factors associated with the prevalence of diarrhea and respiratory disease (BRD) in calves. Cleanliness was important. High bacteria counts in milk at the nipple, AMF internal cleaning < 3 times daily, and wet bedding surface were associated with greater disease prevalence. Conversely, feeding milk replacer at > 13% solids, addition of probiotics to milk replacer, and provision of fresh bedding every 2 to 3 days were protective. Calves' milk intake (reduced total daily volume and

as a percentage of their maximum allowance), slower drinking speed, and failing to have 2 or 3 unrewarded visits per day to the AMF were associated in the short term (next one day or so) with incident scours or BRD.³⁵ No one sensor-based indicator provided discrimination, but in parallel sensitivity was up to ~ 80%, albeit with poor specificity. Therefore, with further development of algorithms, data from AMF may at least be useful to screen calves for closer examination. A recent study³⁶ used similar AMF data and various machine-learning algorithms to achieve accuracy of disease prediction (F1 score) up to 75%.

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