State-of-the-art sensors to monitor/manage dairy calf birth and calf health

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SUMMARY

The two most hazardous periods in the life of a dairy animal are birth and the pre-weaning period. Birth presents the highest risk of mortality and the pre-weaning period presents the highest risk of morbidity for the dairy calf. Hence, it is the breeder's responsibility to ensure calves transition successfully through these two high risk periods. Traditionally this was accomplished by good breeder stockmanship. However, as dairy herd sizes increase and skilled labour becomes less available, alternative approaches to protecting good calf health and welfare are required. One approach under active research currently is to utilise modern technologies to assist the breeder in monitoring and managing calf health from birth to weaning. After years of developments in precision livestock farming (PLF) technologies for dairy cows, now PLF technologies are increasingly being adapted and validated for dairy calves. The international state-of-the-art in three current active areas of research are reviewed here; prediction of calf birth, prediction of neonatal calf diarrhoea (NCD) and prediction of bovine respiratory disease (BRD) in calves through use of 'on cow/calf', 'in cow/calf' or 'off cow/calf' sensors. The focus of commercially available birth prediction devices is across monitoring dam activity, body temperature, tail elevation and foetal expulsion. The merits and demerits of each approach is discussed and summarised. For both calf diarrhoea and respiratory disease while there are studies on measurement of calf activity and physiological parameters, the focus currently is on utilising feeding/drinking behaviour data from automatic feeders. To date much of the output from this research has *retrospectively* associated parameters with subsequent ill-health but has not *prospectively predicted* ill-health. Major future challenges for all PLF calf technologies include validation of existing commercial devices, integration of information across different devices and development of economical, *real-time*, decision support forecasting tools for commercial dairy breeders. Thus, while multi-technology approaches show better results than single techniques, they are also less economical currently. Given that research on dairy calf PLF lags behind dairy cow PLF research, these early technology adaptation problems are to be expected; next generation calf-specific PLF technologies may resolve these issues and make such devices mainstream for dairy breeders.

KEY WORDS

Prediction; Automatic feeder; Calving; Calf diarrhoea; Respiratory disease.

INTRODUCTION

Both lack of (aging breeder population, reluctance of younger generations to work on farms) and limitations in (basic knowledge and skills) farm labour (including increased costs) and increased herd sizes has led to increased on-farm usage of biosensors to assist breeders in dairy cow management. This is a rapidly evolving area, part of the Precision Livestock Farming (PLF) revolution. Recent rapid advances in biosensors, artificial intelligence and Bluetooth and cloud-connectivity have heralded this technological revolution. In particular, machine-learning algorithms (a subfield of artificial intelligence; AI) have greatly improved our ability to differentiate signal from noise in big datasets (1). This, allied to the aggressive commercialisation of biosensors, as in the explosion in wearable wellness human devices, has hastened their use in farming. Thus, on modern, large dairy farms, sensors are increasingly being utilised as day-to-day farming management decision support tools.

To date, most of the bovine biosensors available have been developed for cows, primarily dairy cows and primarily lactating dairy cows (2), not calves. This has been driven by the demand for automated oestrous detection in large dairies. This is now changing. Increasingly biosensors are being tested for use on calves. While the hardware technology is rapidly advancing, current research gaps include information integration and development of real-time decision support forecasting tools (3). In addition the role of individual calf personality on their behaviour (4) and hence the usefulness of the latter to predict calf ill-health requires further research. A more prosaic issue with PLF technology is breeder failure of confidence in the face of multiple false alerts leading to him/her ignoring alerts altogether (5). Regarding calf health, three areas are of current active research interest: prediction of the time of calf birth, prediction of calf diarrhoea and prediction of calf respiratory disease. The state-of-the-art in biosensors to monitor/manage these three areas is reviewed here.

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PREDICTION OF CALF BIRTH

Calving sensors will potentially bring accurate, real-time prediction of not only the time of calving, but also whether dystocia or stillbirth is likely, within reach (6). A recent survey of veterinarians has shown that while they had good practical knowledge on the use of these devices on cows, they may have less knowledge on the accuracy/positive and negative predictive values of such commercially-available devices (7). More than a dozen indicators of impending parturition have been tested to develop calving alarms; four of the most researched approaches are reviewed here.

Activity monitors

The activity patterns of pregnant cows change in the days and hours before calving. The decline in time spent ruminating was found to be a better predictor of calving time (within 4 h) than time spent feeding as while the former drops dramatically on the day of calving, the latter progressively declines as early as ten days prepartum (8, 9 10). Posture changes were found to be more indicative of onset of calving than all others in the prepartum ethogram (11). However, even recording combinations of rumination time, lying time and lying bouts simultaneously was insufficient to precisely determine the onset of calving (12). The highest balanced accuracy of monitoring multiple activities precalving using an ear-attached accelerometer was 74% at one hour precalving but the sensitivity (Se) was only 0.19 (13). The limitations of smart-tag data to predict calvings accurately were also highlighted in a recent large scale study (14). Better results were achieved with a noseband sensor and leg accelerometer recording multiple activities; Se 0.85-0.89 and specificity (Sp) 0.74-0.93, for prediction within 3 h of calving (15). A combination of activity and rumination sensors was able to predict the day of calving (Se 0-1.0, Sp 0.87-0.99 depending on the model) and within 8 h of calving (Se 0.59-0.80, Sp 0.75-0.93), (16), though this 2-technology approach was not economical. Examples of activity monitors include IceQube, Hi-Tag, HR-tag, RumiWatch, Silent Herdsman Collar, MooMonitor, SensOor and Smartbow ear tag.

Foetal expulsion monitors

The emergence of the foetus and/or the amniotic sac presages the completion of calving (stage two) by minutes to hours. There is only limited research on the ability of foetal expulsion sensors to predict time of calving. A vaginal photosensor triggered by expulsion into ambient light detected expulsion of the chorioallantoic sac earlier than barn staff and correctly signalled the onset of calving in 78% of heifers with a Se of 0.78 and a Sp of 0.93 (17). However, the device was not well tolerated by all heifers, particularly when *in situ* for more than 24 h, and led to dystocia and endometritis, poorer fertility, milk yield and increased culling (18). Additionally, both loss of the device and false alarms were a problem in multiparous Simmental, but not Holstein-Friesian cows (19). A vulvar lips separation mechanical signal device detected the onset of foetal expulsion with a Se of 1.00 and a positive predictive value (PPV) of 0.95 and allowed farm staff to attend all monitored calvings apart from 5% with false alarms (20). In a larger study, use of this device was associated with a reduction in stillbirth, RFM and metritis in the monitored cows (21). A number of commercial devices have been developed to detect the expulsion of the foetus including Cow Call, C6 Birth Control, GPS-Calving Alarm, iVET and New Deal.

Tail elevation monitors

The frequency and duration of horizontal tail raising increases in the hours before calving. Significantly more tail raises occur within six hours of calving than before (22). This prediction window was confirmed using a tail-mounted accelerometer with a Se and PPV of 0.96 (23). Follow on studies showed that the increased duration of tail elevation occurs earlier in heifers (4 h) than in cows (2 h) but that eutocia could not be differentiated from dystocia (24, 25). In contrast, a later small (n=20) study showed that dystocia may be predicted (Se 0.77, Sp 1.00) from tail raise duration and frequency (26). A more recent small (n=14) study using a tail-mounted accelerometer found correct prediction of calving in 92% of cows (27) while a PPV of 0.5 was reported in cows (n=38) at 24h prior to calving (28). However, a larger study (n=73) revealed high rates of no alerts (18%), and false alerts (50%), using the same device (29). The largest study in dairy (n=110) and beef cows (n=144) concluded that a tail sensor could predict calving with 90 and 60% accuracy at one and six hours precalving, respectively (10). The most recent study (30) found high false positive and high device drop rates (despite the addition of elastic wrap to secure the device to the tail) and concluded that these problems may compromise commercial applicability. A number of commercial devices are now available: Alert'Vel, Animal Sensing, Calving Alert Set, Moocall sensor, and SmartVel.

Temperature monitors

The body temperature of the pregnant cow declines in the 48 h before calving. The most accurate indicator of impending calving using reticulo-rumen temperature is a drop of >0.2°C within 24 h of calving (31, 32). One study reported 100% accuracy and 93% specificity in predicting time of calving within 24-48 h of calving using a reticular temperature drop of 0.4°C (33). Using a vaginal temperature drop of >0.1°C over 24 h, calving time was optimally predicted within 24 h with a Se and Sp of 74% and PPV and negative predictive value (NPV) of 51 and 89%, respectively (12). The authors concluded that precise prediction of time of calving was not possible using either vaginal temperature or a combination with lying time and rumination time. A similar conclusion was reached by in a study using daily rectal temperature recording, due to the wide variation in the temperature decline between cows (34). Most interestingly, recent studies found that reticuloruminal and vaginal temperatures dropped earlier precalving in cows that subsequently had dystocia than those with eutocia (35, 36). Additionally, use of a vaginal temperature monitor could be associated with a reduction in dystocia, stillbirth, RFM and clinical metritis rate (36, 37). Numerous commercial devices have been designed which incorporate thermosensors to predict calving time: CowsOnWeb, Gyuonkei, HK Calving Alarm, MooMinder, Radco, Smaxtec, Tsense, Vel'Box and Vel'Phone.

Summary of calf birth predictors

Of activity monitoring devices, a combination of rumination time and posture changes appears to offer the best prediction accuracy but cost may be an issue for some breeders not already using PLF technology. Of foetal expulsion devices, vulval lips separation devices appear to offer the best prediction accuracy but these must be attached by a veterinarian. Of tail elevation devices, tail mounted accelerometers appear to offer the best prediction accuracy but issues with tail injuries and no/false alerts may occur. Of thermosensors, intra-vaginal devices appear to offer the best prediction accuracy but the animals must be restrained and the devices inserted hygienically in the vagina. Currently there are no published studies comparing all available commercially-available devices together so we must rely on studies where one device is compared with breeder observations or where more than one device is compared on the same animal.

PREDICTION OF NEONATAL CALF DIARRHOEA (NCD)

Diarrhoea is still the number one cause of mortality in neonatal calves (38). Given the significant long-term effects of NCD on productive and reproductive performance (39), breeders have long wished for a reliable way of predicting which calves will get diarrhoea in time for them to treat early. Traditionally, breeders observe calves for clinical signs of diarrhoea, whether that is sickness behaviours (e.g. slow to drink), or signs of ill-health (e.g. dehydration). However, calves are stoic animals so signs can be subtle and by the time clinical signs are detected visually irreversible intestinal pathology may already have occurred. This problem is exacerbated in modern large-scale dairies where 100s-1,000s of calves are reared by limited labour units with limited time to observe individual calves twice daily for signs of ill-health.

Hence, numerous predictor variables have been explored to detect the onset of NCD. These include feeding/drinking behaviour (e.g. 40), activity behaviour (e.g. 41) and physiological parameters (e.g. 42). Given that the prevalence of NCD can be low on some farms, this can lead to a high proportion of false positive alarms (43).

Feeding/drinking behaviour

While traditionally data on calf behaviour have been collected on research farms using video camera time-lapse technologies, the recent increased use of automatic feeders (AF) for calves which can collect health-associated parameters has opened up new methodologies to monitor calf behaviour on commercial farms. As calves with diarrhoea will have reduced appetite, the objective of predictive studies is to detect metrics of this in altered behaviour before the clinical signs of diarrhoea are apparent to the breeder. Typically, these studies monitor behaviours such as milk or milk replacer consumption, drinking speed and number of visits (rewarded/unrewarded) to the AF. To date these studies have shown promising results. For example, a recent trial on two dairy farms found that calves with diarrhoea had fewer rewarded visits to the AF at the time of diagnosis and consumed less milk in the week post-diagnosis (44). Previous studies have detected differences in milk consumption, drinking speed and unrewarded visits up to four days prior to or on the day of diagnosis of diarrhoea (40, 45). However, though statistical differences were detected between diarrhoeic and control calves in these studies, even applying statistical process control techniques to feeding behaviours alone are not sufficiently accurate (low Se and Sp) to achieve widespread clinical utility to predict diarrhoea (40). An added complexity is the difference in predictor variables between feeding systems. For example, drinking speed was the best predictor variable in ad lib-fed calves while number of unrewarded visits was the best predictor in restricted-fed calves (43). However, such altered behaviour might be an early warning, in conjunction with other predictors, for breeders to observe/examine calves with altered feeding behaviour more closely.

Activity behaviour

As with feeding/drinking behaviour, calves with diarrhoea have altered activity patterns which may be detectable prior to the onset of clinical signs. The recent advances in accelerometer technology (e.g. ear or leg-mounted) has allowed researchers to measure these behaviours, such as standing/lying/step activity and standing/lying bout times, noninvasively, on large numbers of calves. The most recent study, using ear tag-based accelerometers in calves to predict diarrhoea, found that affected calves had reduced activity and increased lying time in the day pre-diagnosis of NCD (41). The authors concluded that lying time in the day pre-diagnosis had a fair ability to predict diarrhoea, with acceptable Se and Sp, however, further research was still warranted. Leg-mounted accelerometers (pedometers) detected less calf locomotion activity (fewer steps, lower activity indices, i.e. greater lethargy) up to two days before diarrhoea with variable effects on lying bouts prior to diagnosis of diarrhoea (46, 47).

Physiological parameters

Individual research studies have tested individual physiological parameter monitoring devices, but there are currently no widely used, validated, commercially available systems. Potentially, calf body temperature can be monitored, e.g. using indwelling rumen boluses, ear temperature sensors or infrared thermography (42). Given potential welfare issues with attaching sensors to animals, non-contact detection technologies have grown hugely in recent years for animal uses, e.g. IRT, image processing, microwave telemetry, acoustic detection and machine vision (48). Similarly, rumination behaviour and pH can be monitored. However, validation studies are required as extrapolation of results from adult ruminants may not be appropriate in pre/pseudo-ruminant calves. Calf heart rate/variability can also be measured but to date the technology is not suitable for commercial use nor is it validated for disease prediagnosis, being primarily linked to painful events, e.g. disbudding (1).

Summary of calf diarrhoea predictors

Of calf feeding/drinking monitoring technologies, those based on data collected from the automatic feeder appear to offer the best potential but none as yet can accurately pre-diagnose NCD. Of calf activity monitoring devices, ear or leg-mounted accelerometers appear to offer the best prediction accuracy but none as yet can prospectively predict the onset of NCD. Of calf physiological parameter monitoring devices, body temperature and rumination activity appear to offer the best prediction accuracy but both need validation studies.

PREDICTION OF BOVINE RESPIRATORY DISEASE (BRD) IN CALVES

Similar to calf diarrhoea, feeding/drinking behaviour (e.g. 49), activity behaviour (e.g. 50) and physiological parameters (e.g. 51), have been used, sometimes in combination, to attempt to predict the onset of BRD. The majority of research in this field is now focused on data from AF studies since the earlier studies have shown the potential for these data to predict all-cause calf diseases (52). While the reference standard for 'BRD' varies between studies, increasingly thoracic ultrasonography +/- clinical scoring is now used to define a case of BRD (53). Early diagnosis of BRD could facilitate earlier therapy thus optimising treatment outcomes. Additionally, automatic prediction of relapsing calves may be possible before re-manifestation of clinical BRD (54). Recent machine learning modelling in this field has demonstrated the tradeoffs between breeder observations and PLF based on AF-generated data with the former more accurate in low-budget scenarios and the latter in high-budget scenarios (55).

Feeding behaviour

The most recently published study on prediction of BRD using AF and accelerometer data on altered calf behaviours found that automated data were highly accurate up to six days pre-diagnosis of clinical BRD (49). In this study precision technologies were combined with machine learning (ML) algorithms. Previous studies using ML for the same application had produced only moderate accuracy of diagnosis (e.g. 56) or concluded that monitoring AF feeding behaviour was not an effective method of identifying subclinical BRD (57). In contrast, an earlier study found that both the number of unrewarded visits to the AF and energy intake were altered pre-diagnosis of BRD thus feeding behaviour can indicate cases of BRD (58). However, the feeding behaviour of limit-fed calves differs from ad-lib-fed calves (59) which has implications for BRD detection. Hence, further replication is required across different calf-rearing systems. A greater challenge now is to replicate promising findings in *real time* rather than in post hoc data analyses.

Activity behaviour

Though variation exists in research results, BRD has generally been associated with fewer daily steps and fewer lying bouts prior to diagnosis (42, 50). Effects of BRD on lying duration are variable; in some studies there were no effects on lying time, (50) while in others diseased calves lay for longer and tended to have longer lying bouts (60). Thus PLF technologies appear to mirror the observations of breeders regarding the variably altered activity of calves with BRD, but the challenge for these technologies is to detect these behaviours *before* the breeder can.

Physiological parameters

Unlike NCD, monitoring physiological parameters has been used successfully to predict BRD. For example, infrared thermography (IRT) can detect an increases in eye or shoulder temperature up to four to six days before BRD (42, 51). This technology can, experimentally, be installed in a water or feeding station (61). However IRT has the disadvantages of inconsistency in anatomical site temperature changes and as a 'stand-alone' technology of lacking integration into overall animal/calf disease prediction pre-diagnostic systems. In addition to monitoring physiological parameters, more overt signs of BRD can be monitored, e.g. coughing. Technology (and algorithms) already exists to automatically detect coughs using sound monitoring technology (acoustic sensors) and this has been shown to have moderate sensitivity and high precision (1, 62). While commercial cough detection is now possible in piggeries, this is not yet used in commercial calf farms but this is a technology with future potential. In addition to these advances in prediction of BRD, the most significant advance in the last decade has been the improved accuracy of diagnosis of BRD, specifically, the use of thoracic ultrasonography (TUS) for both early diagnosis (63) and for monitoring response to pharmaceutical interventions, e.g. antimicrobials/NSAID (63) or vaccines (64).

Summary of calf respiratory disease predictors

Of calf feeding/drinking monitoring technologies, those based on data collected from the automatic feeder appear to offer the best potential but need to be interpreted in light of calf feeding system, i.e. limit-fed vs ad libitum fed. Of calf activity behaviour monitoring devices, those based on ear- or leg-mounted accelerometers appear to offer the best potential but results to date have been variable and conflicting. Of physiological parameter monitoring technologies, those based on infra-red thermography and cough detection appear to offer the best potential but none are as yet commercially validated for dairy calves

Conflicts of interest

The authors declare that they have no conflict of interest.

Authors Contributions

All Authors who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the conception and design of this work or the analysis and interpretation of the data, as well as the writing of the manuscript, to take public responsibility for it. Authors believe the manuscript represents valid work. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication.

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