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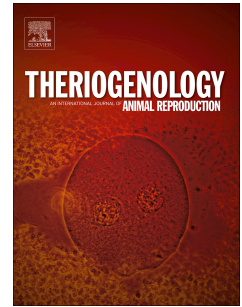
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1

2 Potential of connected devices to optimize cattle reproduction3 Marie Saint-Dizier¹, Sylvie Chastant-Maillard²

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8 Estrus and calving are two major events of reproduction that benefit from connected devices
9 because of their crucial importance in herd economics and the amount of time required for
10 their detection. The objectives of this review are to: 1) provide an update on performances
11 reached by sensor systems to detect estrus and calving time; 2) discuss current economic
12 issues related to connected devices for the management of cattle reproduction; 3) propose
13 perspectives for these devices. The main physiological parameters monitored separately or in
14 combination by connected devices are the cow activity, body temperature and rumination or
15 eating behavior. The combination of several indicators in one sensor may maximize the
16 performances of estrus and calving detection. An effort remains to be made for the prediction
17 of calvings that will require human assistance (dystocia). The main reasons to invest in
18 connected devices are to optimize herd reproductive performances and reduce labor on farm.
19 The economic benefit was evaluated for estrus detection and depends on the initial herd
20 performances, herd size, labor cost and price of the equipment. Major issues associated with
21 the use of automated sensor systems are the weight of financial investment, the lack of
22 economic analysis and limited skills of the users to manage associated technologies. In the
23 near future, connected devices may allow a precise phenotyping of reproductive and health

24 traits on animals and could help to improve animal welfare and public perception of animal
25 production.

26 Keywords (5 max): estrus – calving – –monitoring – prediction - sensor

27 Cattle reproduction ensures meat and milk production together with herd replacement.
28 Reproductive events have to be precisely monitored to improve both the management and the
29 economic performance of cattle herds. Estrus and calving are the most sensitive steps: they
30 require time for their detection and once detected, crucial decisions, including insemination
31 and human intervention for newborn delivery, have to be made. There is evidence that the
32 sensitivity of estrus detection by visual observation (3 periods of 20 minutes each, every day)
33 of behavioral signs is limited (50-60%) [1-3]. Furthermore, the visual detection method is
34 made more challenging by the short duration and low intensity of estrus signs in modern dairy
35 cows , the increasing herd sizes and the limited availability of labor time per cow [4-6]. These
36 two last factors have also probably contributed to the increase in the prevalence of dystocia
37 and stillbirths in dairy cattle. In Holstein dairy cows in the USA, the proportion of calvings
38 with a calf born dead at term or dying 24 h after birth is high, around 8%, and the rate of
39 calvings considered dystocic reaches almost 14% [7-9].

40 In that context, sensors, i.e. devices measuring a physiological or behavioral parameter of
41 individual cows and enabling automated, on-farm detection of its changes (also called
42 “connected devices”; figure 1) [10], are potent tools for estrus and calving management in the
43 field (figure 2). The objectives of this review were to: 1) provide an update on performances
44 reached by sensor systems to detect estrus and calving time; 2) discuss current economic
45 issues related to connected devices for the management of cattle reproduction; 3) propose
46 perspectives for these devices. Sensors measuring a physiological parameter on animals but
47 with yet no automated data transmission, such as thermal cameras, estrus patches or blood

48 assays, were considered off topic. In addition, even if field data may be available for some of
49 them, only connected devices supported by published scientific data are being reviewed.

50 **I. Performances of connected devices**

51 Connected devices, are, like diagnostic tests, characterized by their sensitivity, specificity,
52 positive predictive value (PPV) and negative predictive value (NPV). Nevertheless, the
53 criteria on which the diagnostic value is to be evaluated may vary according to the
54 practical objective of the device. For calving time prediction, sensors with high sensitivity
55 (i.e. expressed by a high proportion of cows) are preferable with the trade-off of more
56 false alarm (low specificity), in order to avoid human absence during calving needing
57 assistance. The devices are also expected to be of high NPV (i.e. a high proportion of
58 cows who do not express the monitored sign and do not calve during the 12 coming hours
59 for example), for the farmer to limit surveillance especially at night. For estrus detection, a
60 confirmation of estrus (by visual observation of physical signs) is often performed before
61 AI: in that case, the sensitivity of sensors is more important than its specificity since in
62 case of false positive, the AI will not be performed.

63 **I.1 Estrus detection**

64 **I.1.1. Physiological modifications at estrus**

65 Estrus in cows is associated with several behavioral and physiological changes, yet
66 with high variability between females due to environmental, herd and cow factors [6]. On the
67 endocrine level, estrus is preceded by luteolysis, i.e. a rapid drop in milk and blood
68 progesterone concentration. An average interval of 80 h was found between the drop in milk
69 progesterone level below 5 ng/ml and ovulation in lactating dairy cows, however this interval
70 was highly variable between individuals, ranging from 54 to 98 h [11]. The unique estrus-
71 specific behavior is the standing-to-be-mounted behavior. However, this behavior is

72 expressed by only approximately 60% of housed modern dairy cows [4, 5]. Mounting
73 behaviors, although not estrus-specific, were reported to be more frequent than mounting
74 acceptance behaviors during estrus and were recorded to occur in 90% of estrus periods in
75 cattle [5]. The global activity of the cow, defined as the number of steps or the total number of
76 animal movements, is also increased during estrus. Recorded thanks to pedometers in
77 Holstein cows housed in a free stall, number of steps started to increase on average 29 h,
78 ranging from 22 to 39 h, before the time of ovulation [12]. However, up to 10% of lactating
79 dairy cows do not exhibit any increase in activity before ovulation [13]. In parallel to this
80 increase in activity, the body temperature transiently increases of around 0.3°C-0.4°C at the
81 time of estrus compared to the luteal phase, in both cold and hot seasons [14, 15].

82 Connected devices designed for estrus detection are based on the monitoring of these
83 behavioural and/or physiological parameters considered separately or combined.

84 **I.1.2. Monitoring of the standing-to-be-mounted behavior**

85 The standing-to-be-mounted behavior may be detected by a rump-fixed pressure sensor with
86 radiotelemetric transmission of mounting data (available under the name HeatWatch® DDX
87 Inc., Denver, CO). Overall, the reviewed performances of HeatWatch ranged from 37 to 94%
88 for sensitivity (defined as the rate of correctly detected estrus periods among all estrus
89 periods) and from 77 to 100% for predictive positive value (PPV, defined as the rate of
90 correctly detected estrus periods among all emitted alerts) [16, 17].

91 Comparison between Heatwatch and visual observation for estrus detection gave discordant
92 results, probably due to differences in breeds and management systems. In beef heifers kept
93 outdoors, no difference was evidenced between Heatwatch and a twice daily observation [18].
94 Compared with thrice daily visual observations in dairy cows, the efficiency of estrus
95 detection using Heatwatch was reported to be lower [19] or higher [1] on pasture, and

96 equivalent [20] or higher [1] indoors. Moreover, Heatwatch sensitivity and PPV were found
97 lower in housed dairy cows than in pastured cows, with false positives due to the pressure of
98 the device against side bars of individual cubicles in housed cows [1]. Furthermore, it has
99 been reported that patches could come off or become displaced during mounting, resulting in
100 missed data [19].

101 Another system, developed in New Zealand, detects mounting acceptance thanks to a
102 traditional pressure-sensitive device (such as Kamar ®) but with an automatic camera-
103 recognition of its status (either missing, not-activated, or activated) at every milking session
104 [21]. The sensitivity of this camera-based system was comparable with that of visual
105 observation or Heatwatch but the PPV was slightly lower [21].

106 A new approach to identify estrus behaviors may be cow positioning in space using ultra-
107 wideband (UWB) radio technology [22]. Indoor, UWB technology can record positioning of a
108 mobile unit with centimeter accuracy in the horizontal and less than 30 cm vertically. The
109 analysis of 3-dimensional positions of 12 dairy cows with synchronized estrus and housed in a
110 free-stall barn allowed the detection of both mounting and standing-to-be-mounted behaviors
111 during estrus. Based on both behaviors, only one false positive out of 10 alerts was obtained
112 [22]. These preliminary findings require confirmation in a larger number of animals and under
113 various housing conditions.

114 **I.1.3. Monitoring of global activity**

115 Automatic activity monitoring systems (AAMS) for estrus detection consist in pedometers,
116 neck-collar mounted activity-meters and 3D-accelerometers attached to the leg or the neck
117 [16]. AAMS have been extensively tested in commercial indoor dairy farms [2, 3, 23, 24] as
118 well as in pastured production systems [25-27] and their performance for automated estrus
119 detection has been reviewed [16, 17, 28]. Using milk or blood progesterone serial assays as

120 gold standard to identify the occurrence of estrus, the sensitivity of AAMS ranged from 59 to
121 94%, their specificity from 90 to 100% and their PPV from 36 to 92% (Table 1) [2, 17, 25-27,
122 29, 30] . Compared with the visual observation (2 to 6 times a day, 10-30 min/observation) of
123 estrus behaviors, AAMS were reported to be of equivalent [31] or higher [2, 3, 32] sensitivity,
124 with less false positives [2, 3, 32]. In farms where cows are equipped with AAMS, the
125 usefulness of maintaining visual observation to improve estrus detection rate is questionable.
126 When both AAMS and visual detection were used in parallel, the sensitivity was higher than
127 with AAMS alone but the PPV was decreased [3, 32] or not modified [2]. Few studies
128 evaluated the relative performance of various AAMS devices in the same animals [2, 24, 33,
129 34]. From those studies, no clear conclusion can be reached regarding differences in
130 performance between collar- and neck-mounted accelerometers.

131 A wide range of factors influencing the performance of connected pedometers and
132 accelerometers for estrus detection, including methodological, technical or biological factors,
133 have been identified and recently reviewed [17]. A constant methodological factor of variation
134 among studies is the way a true estrus is defined. For instance, taking the visual observation
135 of behavioral signs of estrus or the day of insemination to define a true estrus episode will
136 underestimate the rate of silent ovulations and generate less false alarms than the use of serial
137 milk or blood progesterone measurements, which give a reliable indication of ovulation [17,
138 28]. Regarding the technical aspects of the devices, the period, the time window for activity
139 measurement and the threshold used in the algorithm to define an increase in activity as
140 indicative of a true estrus consistently impact the performances of AAMS [12, 26, 29, 35].
141 Default thresholds values and algorithms are often set by manufacturers in marketed devices.
142 Lowering the activity threshold, when possible, may increase the efficacy of detection but
143 with the trade-off of more false positives, resulting in a lower specificity [25, 30].

144 In addition, numerous biological factors known to decrease behavioral expression of estrus
145 also affect the performance of AAMS. These include the rank of postpartum ovulation, the
146 poorest performance being recorded at the first postpartum ovulation [24, 27]; the milk yield
147 and peak milk production, a lower sensitivity being recorded with high-producing compared
148 with low-producing cows [2, 24, 27]; the body condition score (BCS), cows with higher BCS
149 at the time of estrus being more likely to be detected [2, 3, 27]; the parity, in that the
150 sensitivity was lower with cows in their third than in their first lactation [24]; the uterine
151 health, cows with no uterine infection being more likely to be detected [27]; and lameness, in
152 that AAMS displayed a lower sensitivity in male cows compared with non-lame cows [2, 30].

153 **I.1.4. Monitoring of body temperature**

154 Using a vaginal temperature sensor, the detection rates were 96% and 93-100% for natural
155 and synchronized estrus, respectively, and were higher than or equal to those obtained with a
156 pedometer [15]. Temperature sensors placed in the cows's reticulum as permanent bolus are
157 currently marketed for early detection of health problems. Besides helping in health
158 management, these devices could also be used to improve heat detection. The diagnostic
159 values of such devices for estrus detection require specific study. Clearly, the specificity of
160 such tool in different seasons, environmental temperatures and in case of transient fever has
161 still to be evaluated for estrus detection.

162 **I.1.5. In-line monitoring of milk progesterone**

164 The Herd Navigator system (HN; DeLaval, Tumba, Sweden) automatically collects milk
165 samples at milking robots or parlours to analyze progesterone, lactate dehydrogenase and
166 beta-hydroxybutyrate to detect estrus, tissue damage and metabolic disorders, respectively.
167 When tested experimentally for estrus detection, HN detected 99% of confirmed estrus (for
168 which an AI resulted in a pregnancy) and 93% of ratified estrus (defined by a progesterone

169 profile matching that of confirmed estrus) with a specificity of 94% [36]. An average heat
170 detection rate of 95% was later confirmed in commercial herds in Denmark [37]. However,
171 not much has been published on the field performance of HN system.

172 **I.1.6. Combined indicators to detect estrus**

173 In housed dairy cows, the efficacy of estrus detection was enhanced by combining an AAMS
174 with an automated pressure-sensing device [31] or with a traditional heat patch [2] compared
175 with each system alone. Nevertheless, in pastured Holstein cows and heifers, the combination
176 of activity and rumination data analysis generated more false positive alerts than activity
177 alone [30]. Beyond a reliable demonstration of its technical benefit, the multiplication of
178 sensors in animals may not be economically sustainable.

179 Another more promising approach is the use of automated technologies monitoring several
180 parameters at the same time. Applying machine-learning techniques to data collected by
181 various AAMS in lactating cows, the best performance for estrus detection was obtained with
182 either four continuously recorded behaviors (activity, resting time, rumination and feeding
183 times) or the combined number of steps, lying bouts and lying time collected with
184 accelerometers (Table 1) [14]. However, these data, obtained from a limited number of
185 animals, require confirmation.

186

187 **I.2. Calving detection**

188 The detection of calving time has several objectives: (1) to predict the day before or the actual
189 day of calving which allows to move the parturient cow to an individual maternity pen; (2)
190 to facilitate human surveillance and intervention under good conditions of hygiene and ensure
191 better management of colostrum intake for calves and calf adoption for lactating cows. Thus,
192 the first signal of a connected device for calving time prediction should ideally be delivered
193 before the second stage of parturition, i.e. before the amniotic sac appears at the vulva,

194 because moving a cow just before or during its expulsion can extend the time of delivery [38].
195 A further objective is to be warned of the onset of the calf expulsion and, ideally, of the
196 necessity or not to assist the parturient cow. Indicators providing alerts over different time
197 windows before calving, from a day to a few hours, are thus useful for calving management.

198 **I.2.1. Pre-calving physiological modifications**

199 Numerous behavioral changes have been associated with an impending calving,
200 including restlessness, isolation from the rest of the herd, an increased number of
201 lying/standing transitions and the repeated rising of the tail [39-42]. A decrease in the time
202 spent lying together with an increase in the number of lying bouts were generally recorded
203 over the last one to seven days before calving [43-48]. Thanks to pedometers and
204 accelerometers, it was recently established that these changes generally increase in frequency
205 and peaked in intensity during the last 6 to 12 h before the start of labor [43, 45, 48].

206 Eating and rumination behaviors also change before calving. Evaluated with a
207 noseband pressure sensor, the time spent eating started to decline as early as 10 days
208 prepartum and were minimal on the day of calving [49]. Rumination duration decreases also
209 close to the start of calving in both pasture-based [50] and confinement [46, 48, 49, 51-53]
210 systems, with an abrupt decrease of 20-57% over the last 6 to 10 h before delivery [46, 48,
211 54]. However, depending on the device used, housing conditions and herd management
212 systems, a high variability in prepartum behaviors can be observed between studies [46, 50].
213 In addition to behavioral changes, a gradual drop in body temperature of a few tenths of a
214 Celsius degree is exhibited by both primi- and multiparous cows about 2 days before
215 parturition [55-57].

216 Connected devices currently marketed for calving detection include accelerometers detecting
217 changes in global activity, inclinometers detecting tail raising, temperature sensors and

218 devices inserted into the vaginal cavity or attached to the vulva to detect expulsion of fetal
219 membranes and calf [58]. Rumination sensors initially designed to detect health troubles were
220 also recently evaluated for their ability to predict calving time.

221

222 **I.2.1 Monitoring of activity**

223 Activity monitoring devices initially developed to detect estrus were recently used for an
224 automatic real-time and quantitative evaluation of pre-calving behavioural modifications in
225 dairy cattle [43-45, 47, 48, 50, 59, 60]. The continuous monitoring of lying bouts and lying
226 time, alone or combined, allowed to predict calving time within the next 6 to 24 h but with
227 high rates of false negatives and false positives: a sensitivity of 58% and a specificity of 61%
228 were recorded [48]. By developing an activity index combining the number of steps, lying
229 bouts and standing time, the calving time of Holstein dairy cows and heifers could be
230 predicted on average 6 h before its occurrence (from 2 h to 14h15; more than 4 h in 76% of
231 cows) [45]. Using the same device and applying three different machine-learning techniques
232 to the continuously recorded numbers of steps, lying bouts, lying and standing times during
233 the 21 prepartum days, the actual day of calving could be predicted with high accuracy in
234 Holstein dairy cows (78-89% sensitivity, 94-98% specificity and 42-73% PPV and 99% NPV)
235 [46].

236 Automated image analysis is also a promising tool to detect prepartum behavioral changes
237 (standing, lying, eating and drinking): in a proof-of-concept study on eight cows placed in
238 individual maternity pens, 85-87% of calvings were predicted within 24 hours of their actual
239 occurrence [61].

240 **I.2.2. Monitoring of rumination and eating behaviors**

241 Numerous commercially available data-logging tools (collar-mounted microphone, noseband
242 pressure sensor or 3D-accelerometer) with telemetric data transmission were used to monitor
243 dairy cattle feeding and rumination behaviors before calving [46, 48-54, 62].

244 While the benefit of measuring eating behavior for the prediction of calving still needs to be
245 evaluated in cattle, the performance of automated rumination sensors was recently evaluated
246 for this purpose in dairy cows [46, 48, 50]. Using a collar consisting of an accelerometer and a
247 microphone, a threshold of 10% decline in rumination time gave the optimal combination of
248 70% sensitivity and 70% specificity to detect the day before calving in pasture-based dairy
249 cows [50]. Using the same collar and applying three machine-learning techniques, the day of
250 calving could be predicted with 44-78% sensitivity and 89-95% specificity in housed dairy
251 cows, but with a high number of false positives (PPV of 26-33%) [46]. Thanks to a 3-
252 dimensional accelerometer attached to the ear tag and designed to monitor rumination, the
253 start of calving was best predicted within 6 h but with a poor performance (63% sensitivity
254 and specificity, and only 11% PPV) [48].

255 **I.2.3. Monitoring of body temperature**

256 For purposes of calving prediction, the characteristic prepartum drop in body temperature has
257 been successfully measured by a data-logging apparatus with telemetric transmission placed
258 either in the vagina [48, 56, 63] or in the reticulo-rumen [57, 64] in both beef and dairy cows.
259 Changes in intra-ruminal temperature may be difficult to interpret because of the drop
260 following each water intake [65]. However, in two independent studies, analyses conducted
261 with all data or with the exclusion of temperature values below 37.7°C, i.e. altered by water
262 intake, gave similar results [57, 64]: an average drop of at least 0.33°C was detected over the
263 last two days before parturition [57, 64].

264 A very limited number of studies evaluated the performance of the automatic measurement of
265 body temperature to predict a calving within the next 24 h or less [48, 56, 57]. Based on
266 vaginal temperature, the best indicators of calving within the next 24 h in dairy cows were a
267 cut-off drop of more than either 0.3°C (62-71% sensitivity and 81-87% specificity) [56] or
268 0.1°C (74% sensitivity and specificity) [48]. Using the reticuloruminal temperature, the best
269 test performance to predict calving time within 24 h in dairy cows was achieved with an
270 average drop of $\geq 0.2^\circ\text{C}$ (69% sensitivity and specificity) [57]. In both anatomical areas,
271 increasing the temperature threshold led to fewer false alarms (higher specificity) but lower
272 sensitivity (lower proportion of animals exhibiting the sign), thus a higher proportion of
273 animals that would be missed [56, 57]. For both organs, the prediction of calving within the
274 next 12 h gave slightly more false alarms than a prediction within the next 24 h (specificity of
275 69% and 64% for the vagina and reticulorumen, respectively)[48, 57]. A limitation of vaginal
276 temperature sensors is that they have to be inserted at least 10 days before the expected start
277 of calving for a correct determination of baseline values. Beside the risk of vaginal
278 inflammation, this delay may be difficult to respect regarding the variability in pregnancy
279 duration in cows [66].

280

281 **I.2.4. Combination of measurements**

282 Combining several indicators may maximize the performance of calving prediction in cows.
283 When the data from rumination time and global activity (collected by a collar-mounted
284 accelerometer) were combined with lying and standing activities (lying bouts, lying time,
285 number of steps and standing time collected by a leg-mounted accelerometer) and analyzed
286 using the machine-learning neural network analysis, test performances reach their maximal
287 values, with a sensitivity of 100%, a specificity of 97%, PPV of 60% and NPV of 100%,
288 when compared with each set of data considered alone [46]. Accordingly, the combination of

289 lying/standing activities with vaginal temperature and rumination time (all automatically
290 measured thanks to three different devices on the same dairy cows), gave the best results to
291 predict parturition within the next 6 to 24 h compared to each indicator considered
292 individually [48]. However, as stated above, multiplying sensors on animals is not cost-
293 effective. A single accelerometer attached at the eartag which monitors activity, rumination
294 time, feeding time and ear temperature on an hourly basis was recently evaluated on 400 dairy
295 cows for its ability to predict the start of calving [67]. As expected, the inclusion of these
296 parameters, especially activity, rumination and temperature, improved the accuracy of
297 prediction compared to a prediction based only on the expected date of calving [67]. With a
298 fixed false positive rate of 1% (specificity of 99%), the model developed allowed to predict
299 42% of calvings within a time-window of 3 h and 49% within 6 h [[67]. Overall, the best
300 combination for a prediction of calving within a short time-window (less than 6 h) included
301 body temperature, rumination time [48, 67] and lying bouts [48]. This highlights the fact that
302 the performance of a given indicator varies with its pattern of change and with the time
303 interval chosen to define the alarm threshold. Furthermore, parameters like rumination time
304 and lying bouts change abruptly in the last 6-12 h before expulsion whereas the global activity
305 begins to change earlier [48, 67]. This emphasizes the potential benefit of combining several
306 parameters to provide long-term or short-term alarms.

307 **I.2.5 Automated detection of calf expulsion**

308 Vulvar devices detecting expulsion have to be sutured to the vulval lips of pregnant females
309 close to the calving date. A first part is sutured on the left side of the vulva while a smaller
310 mobile part is sutured on the right side [68, 69]. The engagement of the calf in the birth canal
311 separates the mobile part from the rest of the device and activates a radiowave signal, which
312 triggers, via a receiver-transmitter apparatus, the sending of a text message to a mobile phone.
313 Tested on Holstein cows and heifers in a confinement system, the sensitivity and the PPV

314 were 100 and 95%, respectively [68]. A GPS receiver was added to the device in order to
315 localize the parturient cow in extensive grazing areas [69]. Evaluated in a limited number of
316 animals (18 dairy and 8 beef cows), the sensitivity and PPV of the GPS-localizing system
317 were 100% and the geographical coordinates of the delivering female were correctly
318 transmitted for all cases except one [69]. Nevertheless, since they only detect the second stage
319 of labor, these devices do not fill the first objective of calving prediction mentioned above,
320 that is to be warned before the onset of parturition to be able to move the cow into a calving
321 pen.

322

323 **II. Economic issues of connected devices for cattle reproduction**

324 **II.1. Motivations to invest**

325 Among 832 Canadian dairy farmers, 23% used an AAMS and 10% used it as their main tool
326 for reproduction management for both first and subsequent inseminations (96% of the users
327 applied AMMS to cows, 27% to heifers [70]). Connected devices may be more widely spread
328 in Europe than in other continents due to high employee wages, relatively high prices for
329 hormonal preparations, growing societal concerns regarding the use of hormones in animal
330 production and consumer health, together with society and farmer concerns about animal
331 welfare (linked to repeated drug administration). However, the current use of connected
332 devices for reproduction management in cattle is still poorly documented. Michaelis *et al.*
333 (2014) reported that approximately 1 700 000 automated activity monitoring tags have been
334 sold worldwide and that approximately 100 000 tags are currently used in dairy farms in
335 Germany [3]. Approximately 20% of Dutch [71] and French (C. Allain, Idele, personal
336 communication) dairy farms currently use automated estrus detection.

337 The most frequently reported reason to adopt an AAMS in Canadian dairy herds was the
338 desire to improve herd reproductive performance (81% of respondents) [72]. In decreasing
339 order of answers were then the lack of time to detect estrus (51% of respondents), the chance
340 to monitor health condition along with estrus (45%), the desire to breed cows in natural estrus
341 (44%), the desire to reduce labor (39%), the concern about frequent injections required in
342 timed AI programs (35%), the inability of workers to detect estrus (23%) and going organic
343 (3%) [72]. In Dutch dairy farms, the main reasons for investing in connected devices for
344 estrus detection were improving detection rates, gaining insights into the fertility of the herd,
345 improving profitability of the farm and reducing labor [71].

346 **II.2 Impact on herd reproductive performances**

347 No published data is available concerning the impact of connected devices for calving
348 detection on calf mortality rate or dam post-partum health including reproductive
349 performances. However, the impact of devices allowing automated estrus detection on the
350 global herd reproductive performance was recently evaluated. In the Dutch dairy farms
351 investigated, investing in estrus detection sensors did not change the interval from calving to
352 first service nor the age at first calving [73], probably because the rules on voluntary waiting
353 period and age at first calving were unchanged after the investment. Conception rates for AI
354 performed on estrus detected with mounting sensors were similar in dairy cows [19] but lower
355 in beef heifers [18] than after visual estrus detection. Higher pregnancy rates were reached
356 following inseminations performed in estrus detected with AAMS than after visual detection
357 [3, 74].

358 When comparing the overall reproductive performance between the year before and the year
359 after adoption of an AAMS for estrus detection in 505 Canadian dairy farms, a mean increase
360 of 7% in the 21-day insemination risk (from 42 to 50%) and of 2% in the 21-day pregnancy
361 risk (from 15 to 17%) were recorded, whereas the conception risk per AI did not change [72].

362 The comparison between dairy herds using AAMS and timed-AI for more than 50% of
363 inseminations did not show any difference in pregnancy rates, conception risk and
364 insemination rates [72, 75]. This means that for reproductive management in large dairy
365 herds, AAMS could be an alternative to hormonal synchronization of estrus. However, the
366 new technologies available for estrus detection do not solve the problem of 15-25% cows that
367 fail to ovulate after the voluntary waiting period [76, 77]. For these anovulatory cows, the
368 hormonal induction of estrus may remain the best option.

369 For further improvement of conception rate, some basic knowledge for optimal use of
370 connected devices is also lacking. Manufacturers are expected to provide indications about the
371 delay between data acquisition and data processing to produce the alert, as well as the optimal
372 time to perform AI once the alert is emitted. Short of the latter, the determination of the best
373 time to inseminate relative to the estrus alert is a challenge. The am-pm rule was established
374 in the 40's when estrus detection was only accomplished by visual observation. The earlier
375 detection of estrus potentially offered by automated estrus detection systems compared with
376 visual detection may lead to lengthen the interval between the estrus alert and insemination.
377 Nevertheless, ovulation was observed an average of 27-30 hours after estrus detection by
378 AAMS (with extremes of 21 and 39 hours) and pregnancy rates in dairy cows were reported
379 to be highest with inseminations performed 5 to 18 h after the AAMS alert, as recently
380 reviewed [17]. AI timing seems thus very similar to the 8-to-18-h interval found to be optimal
381 after visual detection of estrus in the field [78].

382 It is of note that automated sensors do not exclude expert human observation of the animals. A
383 clinical examination of a cow detected in estrus by AAMS by the farmer, the inseminator
384 and/or the vet remains necessary to compensate a low specificity of detection of such
385 automated devices. Moreover, the clinical exam remains the only way to detect genital
386 abnormalities preventing insemination, like endometritis.

387

388

II.3 Impact on farm economic performance: return on investment

389 A major issue associated with the use of automated sensor systems for estrus detection is the
390 heavy investment and the payback period [79]. It is noteworthy that the wish of the farmers to
391 limit the investment may affect the performances of the devices. For example, limiting the
392 number of vaginal thermometers may prevent the farmer to insert them long enough before
393 calving.

394 The main reasons given by Dutch dairy farmers [71] and by North Americans [79, 80] for not
395 investing in sensor systems (in general, not only for reproduction management) are
396 economically related. The expected costs for 50 cows is 3-8 k€ for accelerometers,
397 pedometers, vaginal thermometers, abdominal belts, 7-10 k€ for pedometers sensitive to the
398 position (standing/lying) or mounting detectors. HerdNavigator system costs around 50 k€ as
399 an initial investment, to which annual subscription of 55-80 €/cow. To the best of our
400 knowledge, there is currently no data available on the economic outcome of implementing
401 automated calving detection in cattle. Published data on the financial effects of implementing
402 automated systems for estrus detection are scarce but they show globally economic benefits
403 [81-84]. In a recent study, various scenarios of adoption of automated estrus detection were
404 simulated in herds initially using 100% visual detection or 100% timed artificial insemination:
405 the investment was found to be globally profitable and the payback period ranged from 1.6
406 years to more than 10 years, depending on the initial system and labor costs [84]. A user-
407 friendly decision support tool was created by the authors for investment analysis, in which
408 inputs comprise general and reproductive management practices and the cost of the proposed
409 automated system, and outputs include the expected cost per day, the net present value, the
410 pay-back period and the culling rate [84]. In another study, a comprehensive simulation model
411 was used to study the technical and economic effects of implementing an AAMS, in a dairy

412 farm of 130 cows (8,310 kg milk/305 d./cow) in the baseline scenario [83]. Assuming a 30-%
413 increase (from 50 to 80%) in the efficacy of estrus detection with AAMS compared with
414 visual detection and a slight decrease in the specificity of detection (from 100% to 95%), the
415 use of AAMS led to a reduction of 16 days in the average calving interval, an increase in
416 average annual milk production of around 11,000 kg per farm, a parallel increase in the
417 annual number of inseminations (due to the increased numbers of estrus detected and
418 inseminations per calving) and calves, a reduction in the number of culled cows per year and a
419 reduction in labor input [83]. Overall, the investment was profitable, with a difference in
420 annual net cash flow between farms with and without AAMS of 2,827 € over a 10-year period
421 [83]. It is noteworthy that economic benefits depend on herd size. In the previous economic
422 simulation, the marginal financial effect was much lower, of 1,779 €, for a herd of 65 cows,
423 and higher (3,870 €) with a herd of 195 cows [83]. Also, the improvement in herd
424 sustainability when using connected devices clearly depends on the initial performances of the
425 herd (initial estrus detection, dystocia rate and neonatal mortality for calving detection), the
426 cost of the equipment and labor costs.

427

428 **III. Perspectives for connected devices**

429 The development of connected devices not only affects herd performances, as described
430 above, but also raises some technological and societal issues, together with perspectives for
431 the global cattle population (figure 3).

432 **III.1. Toward more polyvalent and easy-to-use systems**

433 Linked to the heaviness of investment, a major challenge of most connected devices for estrus
434 detection is the integration of supplementary data, e.g. on animal production, health, and
435 economic information, into a global management system to generate recommendations, i.e. to
436 inseminate or not a cow in estrus, to isolate a pregnant cow, to intervene or not during calving

437 etc. [10]. With the exception of the HN system, none of the connected devices for estrus
438 detection integrates other information than the parameter monitored. In addition to
439 progesterone assays, the HN system integrates complementary data on the animal, e.g. post-
440 partum interval, milk production, negative energy balance (diagnosed thanks to beta-
441 hydroxybutyrate assays) that are helpful in determining, for each estrus period, a probability
442 of pregnancy if inseminated. The polyvalence of connected devices (i.e. their ability to
443 evaluate other aspects of cow management) is an asset for their practical and financial
444 acceptability in the field.

445 Concerning calving detection, the improper use of calving monitoring systems may lead to
446 premature interventions and expose parturient cow to a higher risk for post-partum genital
447 inflammation and infection. In order to help the farmer to decide to intervene or not, devices
448 should be developed to not only predict precisely the start of calving, but also to evaluate the
449 probability of dystocia in the coming calving. A technology that quantifies the duration of
450 calving from the onset of the first stage, i.e. the time at which uterine contractions begin, may
451 be a first approach to the identification of problematic calvings. To date, no device has been
452 specifically designed to predict abnormal calvings but the first results, based on the
453 continuous recording of prepartum activity, eating and/or drinking behavior, seem promising
454 [58]. Thereafter, algorithms associated with dystocia would have to be incorporated into
455 existing devices.

456 Polyvalence would also meet the need of easy-to-use devices. Lack of technical support and
457 of training for use of automated technologies are major obstacles to investment into connected
458 devices [79]. Among the most frequent reasons given for slow adoption by farmers of
459 automated monitoring systems were the lack of familiarity with technologies and the fear of
460 receiving too much information without any key for converting them into decisions [80],

461 while the simplicity and ease-of-use were frequent arguments in the choice of a new
462 technology to be implemented on the farm [79].

463 **III.2 Phenotyping of reproductive and health traits**

464 Automated monitoring systems make it possible to reach a more precise characterization of
465 reproductive traits in cattle. The numerous connected devices give access to a large number of
466 physiological parameters measured simultaneously in a large number of animals under
467 various management conditions, in a non- (or minimally) invasive way and in a long-term
468 perspective (ideally over the whole life of the animals). Such objective phenotypes are potent
469 tools to explore biological issues underlying the expression of estrus, fertility, but also health.
470 Important questions regarding the interval from the onset of increased activity and ovulation
471 [12], the duration and intensity of estrus in relation to circulating estradiol concentrations [34]
472 were revisited thanks to AAMS. Important questions regarding the interval from the onset of
473 increased activity and ovulation [29], the duration and intensity of estrus in relation to
474 circulating estradiol concentrations [28] were revisited thanks to AAMS. Similarly, AMMS
475 provided the incidence of silent ovulations in Holstein dairy cows under various housing
476 systems [1, 85]. Endocrine fertility traits, defined from progesterone concentrations monitored
477 in milk, have been suggested as alternative indicators for fertility in dairy cows because they
478 are less biased by farm management decisions than classical traits derived from insemination
479 and calving data [86, 87]. The progesterone profiles generated post-partum on a large number
480 of cows allowed to quantify the prevalence of atypical profiles, i.e. abnormalities in
481 postpartum ovarian resumption, in various management situations [88]. In-line milk
482 progesterone monitoring before and after insemination also evidenced a link between the
483 progesterone profiles and the success rate of insemination in Holstein cows [89], underlying
484 their interest for genetic selection on fertility traits in dairy cattle [86, 87].

485 On a population scale, the collection and analysis of these phenotypic data are precious for the
486 selection for estrus expression in dairy cattle. Similarly, the prevention of dystocia relies on a
487 systematic genetic evaluation for calving ease and marker assisted selection for calving traits
488 at the national and international levels [7]. Without automated monitoring, the determination
489 of phenotypes such as difficult calving is only possible through time-consuming observations
490 or subjective evaluation on limited numbers of animals. Connected devices allow the
491 phenotyping of peripartum events in a large number of animals in a variety of environments
492 and management systems and as such, may be useful tools for accurate genetic evaluation of
493 calving ease in cattle and to select females with high genetic index for this trait. A major
494 challenge for sensor systems in reproduction is to integrate a high number of additional data
495 on individual animals and their environment to produce not only more appropriate advice to
496 the farmer, but also robust tools for selection and an integrated understanding of cattle in its
497 farm and management conditions.

498 **III.3 Improving animal welfare and public perception of animal production**

499 Devices that have to be inserted into the vagina and left for several weeks, even months, and
500 vulvar devices detecting expulsion which need a surgical suture to the vulva lips, are
501 questionable in regard to animal welfare. Although the risks for health have not been
502 evaluated so far, vaginal infection, irritation and wall thickening (limiting vaginal dilatation)
503 could be expected with such devices.

504 However, globally, connected devices used for estrus and calving detection offer benefits for
505 animal welfare. The prediction of calving time and accurate identification of cows in need of
506 assistance provide a clear opportunity to improve calf and dam welfare during the peripartum
507 period [90]. It is noteworthy that dystocia is considered by veterinarians as one of the most
508 painful condition for cows [91, 92] and that more than 40% of calvings require assistance
509 [93].

510 Providing a timely appropriate care at calving is crucial for the survival of the newborn calf,
511 for the dam's post-partum health and for the subsequent culling risk [9, 90]. Permanent
512 automated devices could also be helpful to improve the early diagnosis of health disorders
513 during the transition period [51]. Moreover, despite requiring receivers for data collection,
514 connected devices used in reproduction monitoring do not forbid pasture access. Hormonal
515 synchronization of estrus and timed artificial insemination (AI) protocols have been widely
516 adopted in the United States [94, 95] to overcome the time-consuming detection of estrus by
517 visual observation. In Europe, the average size of herds is globally lower and the use of
518 hormonal treatments is less. However, apart from the added cost of treatment, the growing
519 opposition of consumers and producers to the systematic use of hormones, makes hormonal
520 synchronization unacceptable in the management of cattle reproduction. This context gave a
521 specific interest to the automation of estrus detection.

522 By increasing reproduction efficacy, connected devices are expected to increase cow
523 longevity, which is positive from an animal welfare perspective as well as economically. With
524 the increasing concern of public opinion for animal welfare, connected devices have the
525 potential to make livestock farming more transparent and improve the public perception of
526 cattle production.

527

528 **Conclusion**

529 Connected devices for cattle reproduction were initially designed and scientifically evaluated
530 for estrus detection, mainly based on activity, behavioral or hormonal measurements. Their
531 indications now tend to be extended to calving detection, with a marked lack of published
532 validation. Wide perspectives are being opened by these devices in the field of reproduction:
533 beyond improvements in cattle reproductive performance, they may generate improvements in

534 the breeders' quality of life and in animal welfare. They will also contribute to a better
535 understanding of cattle physiology, herd sustainability improvement and cattle selection.
536 Bovine reproduction is thus entering into the era of big data, offering the opportunity of deep
537 insights into physiology, diseases and cow's interactions with its environment. Inevitably,
538 questions regarding the quality and the property of the data generated will have to be
539 addressed in the near future to ensure their optimal valorization.

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783 Figure 1: Operating principle of connected devices. The connected device equipping the cow
784 emits a signal that is processed by a specific software and thereby interpreted by an algorithm
785 into a biological information. In case this information is deviant from thresholds set up by the
786 manufacturer, an alarm is transmitted to the farmer, on a computer and/or on a mobile phone.
787 This alarm implies an action. To be undertaken by the farmer for the cow (insemination,
788 calving assistance)

789 Figure 2: Available sensors for estrus and/or calving detection.

790 Figure 3: Issues and perspectives of connected devices in the field of reproduction.

791 Table 1: Performances of automated activity monitoring systems (AAMS) for estrus detection in dairy cattle.

Parameter(s) monitored	Type of device	Housing conditions	Sensitivity ^a	Specificity ^b	PPV ^c	Number of animals	Ref.
Activity	Collar-mounted accelerometer	Indoors	59%		94%	67	[2]
Number of steps	Leg pedometer	Indoors	63%		74%	67	
Activity	Collar-mounted accelerometer	Pasture	60-70% ^d	99%	68-80% ^d		[25]
Activity	Neck collar activity-meter	Indoors	79-91% ^d	90-98% ^d	40-73% ^d	64	[26]
Activity	Neck collar activity-meter	Pasture	87-94% ^d	90-98% ^d	41-76% ^d	135	
Activity	Collar-mounted accelerometer	Indoors	56-84%	96-100% ^d		647	[29]
Activity	Collar-mounted accelerometer	Pasture	72%		67%	89	[27]
Activity	Collar-mounted accelerometer	Pasture	78-80% ^d	57-94%	67-70% ^d	30	[30]
Rumination	Collar-mounted accelerometer	Pasture	35%	69%	14%	30	
Activity, resting time, rumination and feeding times, ear surface temperature	Ear-attached accelerometer with temperature sensor	Indoors	100% ^e	99-100% ^e	99-100% ^e	18	[14]
Activity and rumination time	Collar-mounted accelerometer	Indoors	60-100% ^e	96-99% ^e	97-98% ^e	18	
Number of steps, lying bouts and lying time	Leg-mounted accelerometer	Indoors	80-100% ^e	98-100% ^e	98-100% ^e	17	
Activity and lying time	Leg-mounted accelerometer	Indoors	100% ^e	90-97% ^e	91-97% ^e	14	

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793 Milk or blood progesterone serial measurements were used as gold standard to confirm estrus events.

794 ^aSensitivity (or efficiency) = true positive alerts (TP)/(TP+ false negative alerts)795 ^bSpecificity = true negative alerts (TN)/(TN + false positive alerts (FP))796 ^cPositive predictive value (or accuracy) = TP/(TP+FP)797 ^dValues vary depending on the threshold and/or the reference period used in the algorithm to define an increase in activity as an estrous period.798 ^eValues were obtained using different machine-learning techniques (random forest, linear discriminant analysis and neural network).

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Milk or blood progesterone serial measurements were used as gold standard to confirm estrus events.

^aSensitivity (or efficiency) = true positive alerts (TP)/(TP+ false negative alerts)

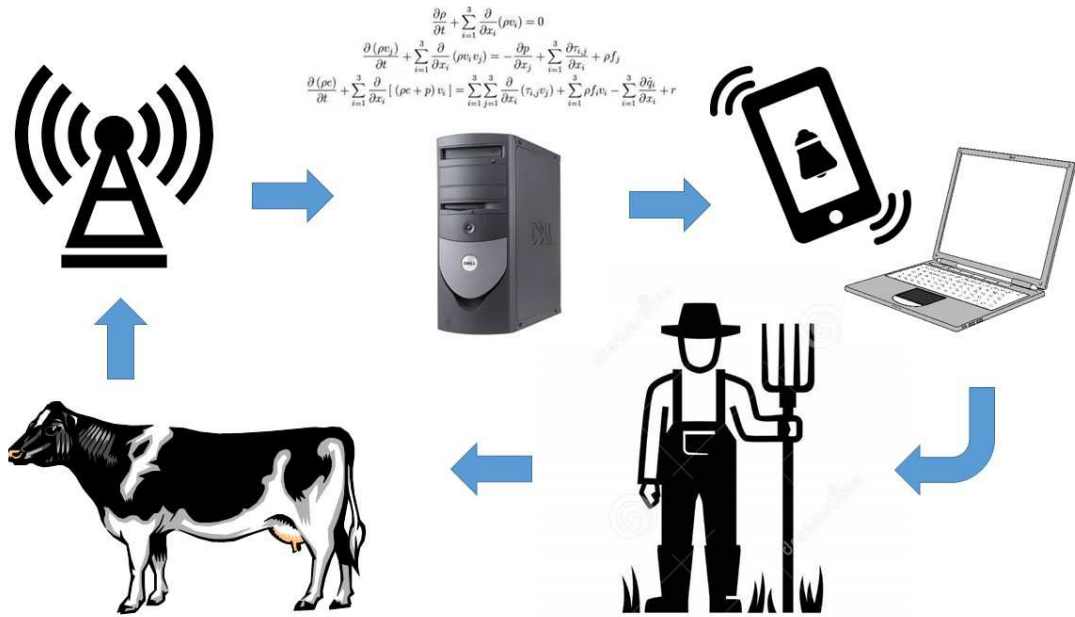
^bSpecificity = true negative alerts (TN)/(TN + false positive alerts (FP))

^cPositive predictive value (or accuracy) = TP/(TP+FP)

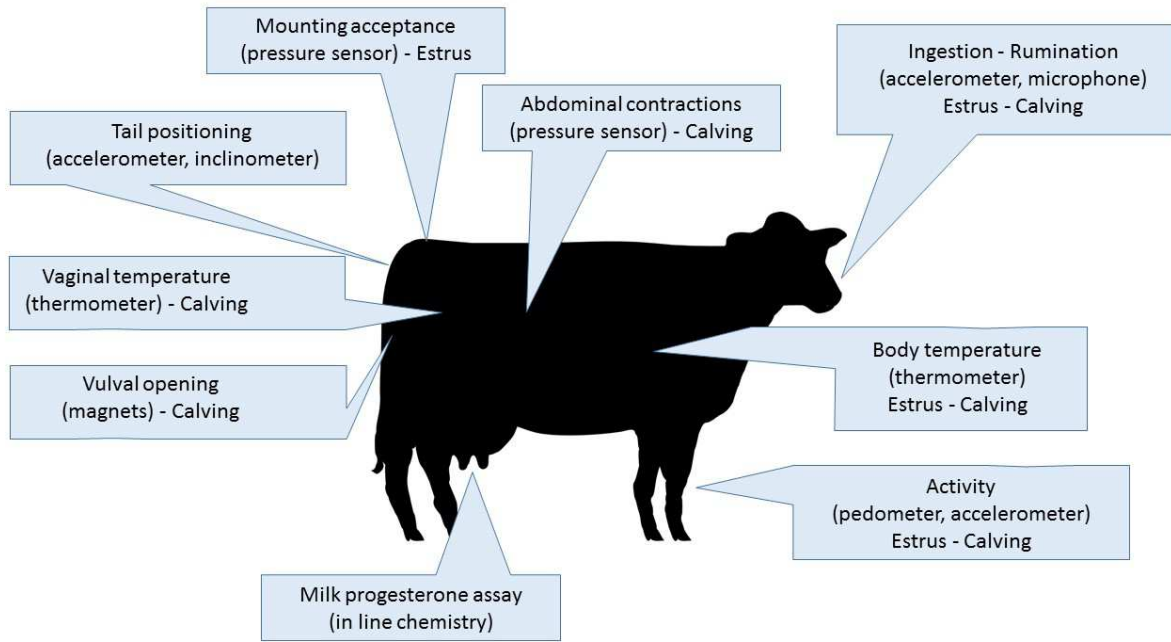
^dValues vary depending on the threshold and/or the reference period used in the algorithm to define an increase in activity as an estrous period.

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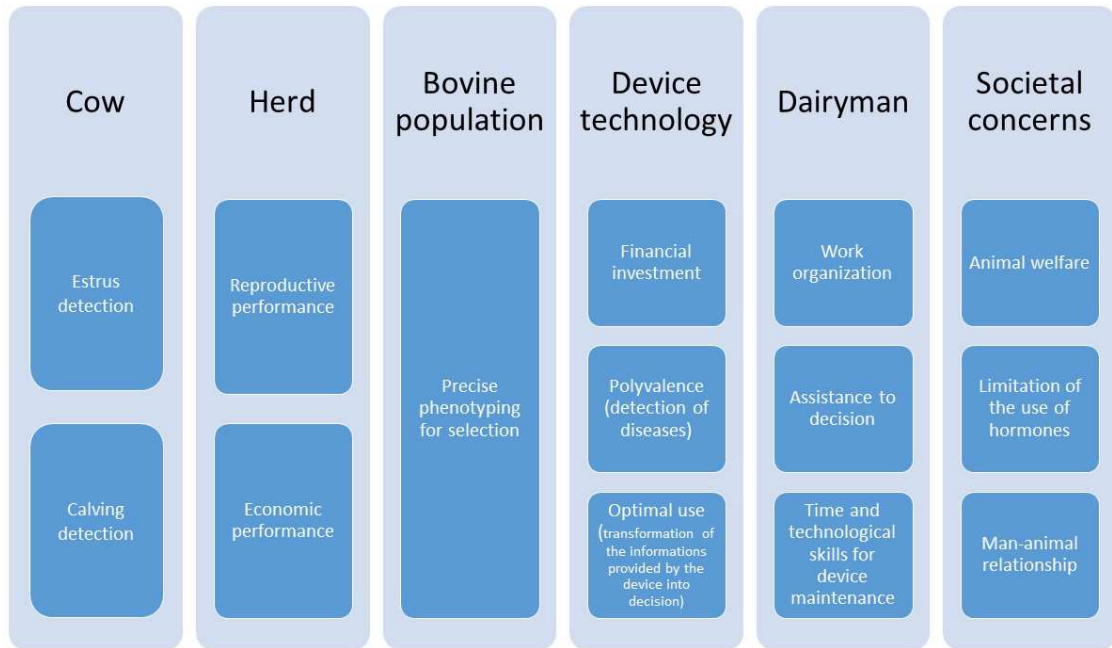
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Highlights

- Connected devices used in reproduction are designed for estrus detection and calving prevision.
- They aim at improving work organization, reproductive performances and animal welfare.
- Activity, ingestion/rumination and body temperature are the most frequently evaluated parameters.
- They represent a potent tool for large scale, non invasive phenotyping of cows in their environment.