Engineering to support wellbeing of dairy animals

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Current trends in the global milk market and the recent abolition of milk quotas have accelerated the trend of the European dairy industry towards larger farm sizes and higher-yielding animals. Dairy cows remain in focus, but there is a growing interest in other dairy species, whose milk is often directed to traditional and protected designation of origin and gourmet dairy products. The challenge for dairy farms in general is to achieve the best possible standards of animal health and welfare, together with high lactational performance and minimal environmental impact. For larger farms, this may need to be done with a much lower ratio of husbandry staff to animals. Recent engineering advances and the decreasing cost of electronic technologies has allowed the development of ‘sensing solutions’ that automatically collect data, such as physiological parameters, production measures and behavioural traits. Such data can potentially help the decision making process, enabling early detection of health or wellbeing problems in individual animals and hence the application of appropriate corrective husbandry practices. This review focuses on new knowledge and emerging developments in welfare biomarkers (e.g. stress and metabolic diseases), activity-based welfare assessment (e.g. oestrus and lameness detection) and sensors of temperature and pH (e.g. calving alert and rumen function) and their combination and integration into ‘smart’ husbandry support systems that will ensure optimum wellbeing for dairy animals and thereby maximise farm profitability. Use of novel sensors combined with new technologies for information handling and communication are expected to produce dramatic changes in traditional dairy farming systems.

Keywords: Dairy technologies, biomarkers, health, welfare, husbandry, review.

Background and current scenario

As if explained by a reverse Malthusian law, the world’s dairy cow milk production has increased exponentially during the last 50 years, whereas the number of dairy cows has increased linearly, with per-cow annual milk yield growing slowly from 1·8 to 2·4 t/cow, on average (FAOstat, 2016). In developed dairying nations the number of cows has been decreasing logarithmically, whilst annual milk yield stands at around 6·5 (EU) and 9·8 (USA) t/cow. The so-called ‘white revolution’ of the EU and USA dairy cow industries has been made possible by significant advances in genetics, breeding technologies and feeding resources, as reported by Capper et al. (2009). Between 1984 and 2015, EU (cow) milk production was controlled at national levels by quotas, with penalties for overproduction and premiums for leaving farming (attractive to older farmers and small farms). This helped to maintain milk prices, but the combination of technological advance and quota caused a shift in the structure, decreasing the number of cows and farms, whilst increasing the total milk yield per cow and per farm. Milk demand is currently fully satisfied in the EU and USA, as well as in Australia and New Zealand, who process their milk surplus to produce skim milk powder for exportation. Milk powder and butter are used to address production deficits of Asia (China and Russia) and, to a minor extent, Africa.

The global scenario is changing. The preference of consumers for liquid milk rather than skim milk powder, the expensive transportation costs of liquid milk and the recent political and economic crises as well as the expansive economy of emerging countries has stimulated several investment initiatives for creating integrated, large-scale dairy farms closer to consumers. In many cases, these dairy farms are located in geographical areas not adequate
for grazing dairy cattle (Mediterranean areas, US Central plains, Asian desserts) and submitted to severe heat or cold stress during part of the year, which requires the development of new farm facilities and highest-quality husbandry practices for high yielding dairy cows. Large-scale dairy farms use the implementation of modern engineering approaches as a way to control the whole milk production process in the farm. Extreme examples of ‘super dairy’ farms are: Vietnam (TH Milk project, 29 000 cows with 7 milking parlours of 2 × 30 stalls), Saudi Arabia (Al Safi, 40 000 cows with 7 milking parlours of 2 × 50 stalls), China (Modern Dairy Co, 40 000 cows, 8 rotary milking parlours) and, most recently, the Russia-China joint development (Zhongding Dairy Farming and Severny Bur, Mudanjiang, 100 000 cow places under construction).

Concurrently with these changes, skilled labour resources in many traditional EU dairy areas have become scarce and expensive because of the rural population exodus. In these cases, farm robots (e.g. automatic milking systems, feeding stations, mobile wagon feeders), based on the use of modern technologies, are often the chosen option to allow financial sustainability for family farms. In practice, the robots allow farmers to organise their working schedule more freely and to devote more time to farm management, so job replacement by robots in dairy farms has hitherto been low. Most economic indices assign considerable positive value to a high number of animals per AWU (annual working unit) which, on average, ranges between 35 and 45 cows/AWU in the specialised dairy farms of the EU (Spicka & Smutka, 2014) and the US (Mugera & Bitsch, 2005), respectively. Similar ratios are not economically sustainable for large-cow dairy farms (1 000 cow units are unlikely to employ 25 staff) but may be needed for large buffalo farms since buffalo are more difficult to handle than cows. By comparison, the ratio for specialised small ruminant dairy farms is greater than 200 head/AWU (i.e. 5 workers/1 000 ewes), as reported by Milán et al. (2011). The economic challenge facing EU dairy farmers remains acute. At the same time that the EU has relaxed quota, the world milk price has fallen, so economy of scale becomes acute. At the same time that the EU has relaxed quota, the world milk price has fallen, so economy of scale becomes acute. At the same time that the EU has relaxed quota, the world milk price has fallen, so economy of scale becomes acute. At the same time that the EU has relaxed quota, the world milk price has fallen, so economy of scale becomes acute. At the same time that the EU has relaxed quota, the world milk price has fallen, so economy of scale becomes acute. At the same time that the EU has relaxed quota, the world milk price has fallen, so economy of scale becomes acute. At the same time that the EU has relaxed quota, the world milk price has fallen, so economy of scale becomes acute.

Dairy animal wellbeing, and the Welfare Quality® programme

‘It is health that is real wealth and not pieces of gold and silver.’ This quote is from Mahatma Gandhi, the engineer of Indian independence and hence the creator of the country with the largest bovine population in the world. Of course, Gandhi had in mind human health, but the aphorism applies equally to animals. The Constitution of WHO (1946) defines good health as ‘a state of complete physical, social and mental wellbeing, and not merely the absence of disease or infirmity’. In animal management we typically aim to avoid disease. To complete the picture to WHO ideals, we also strive for a state of (good) animal welfare, something akin to a welfare state, protecting the wellbeing of our animals (in politics, a welfare state is defined as a system whereby the state undertakes to protect the health and wellbeing of its citizens’). Wellbeing and welfare are in many respects interchangeable terms, but they differ in one fundamental and key way: in common use wellbeing has only one connotation (an optimum state) whereas welfare has many definitions and is used ambiguously and without preface by those who would promote good welfare and those who decry bad welfare. Hence, we prefer to use wellbeing, whilst recognising the usefulness of Duncan and Fraser’s definition of welfare as comprising ‘the state of the animal’s body and mind, and the extent to which its nature (genetic traits manifest in breed and temperament) is satisfied’ (Duncan & Fraser, 1997). Although concerns for animal wellbeing have existed since Neolithic times, the ‘human-animal bond’ being a clue of the domestication process, there is widespread agreement that humans seriously threatened animal wellbeing by the intensification of livestock production systems. Animal protein demand is expected to increase rapidly in the future as a response to human population growth and, consequently, livestock production will grow and intensify more. Animal wellbeing becomes a top priority for EU citizens and in the current livestock policy of the European Commission, as included in its aims for the Horizon 2020 programme. This is also reflected in funding for two FP7 projects, EU PLF (Precision Livestock Farming: EU-PLF, 2016), which includes dairy cattle, and ProHealth (FP7-ProHealth, 2016) which is focused on pigs and poultry.
Dairy animal husbandry refers to the relationship of dairy farmers with their animals and the duty they have to ensure that their animals are given the very best of care whilst trying to optimise their production cycles and lactational performances in a cost-effective way. In the authors’ minds, wellbeing and good husbandry are synonymous, although it is noteworthy that most definitions of animal husbandry pay scant attention to wellbeing.

Whilst wellbeing is important in all production animals, dairy animals have some unique needs derived from their specific characteristics, but also provide some special opportunities for management. For instance:

- Management attention must be geared towards females which have longer expected productive life than most other livestock species
- High-yielding dairy animals have increased susceptibility to heat stress, metabolic problems (ketosis, acidosis, hypocalcaemia), infectious diseases (mastitis, metritis) and multi-factorial diseases (lameness) which are mainly concentrated at specific points in the lactation cycle (peri-partum, early lactation)
- The farmer’s needs for high fertility (early return to oestrous after parturition) and the cow’s needs to avoid additional energetic expenditure may be in conflict
- Technological and biotechnological innovation in automated health diagnostics are more advanced in dairy than in other animal production systems, a number of sensor devices being commercially available at affordable prices
- Regular milking (twice- to thrice-daily) provides opportunities for diagnostic observation

The reality is that productive lifespan averages 2–3 and rarely exceeds 3–4 lactations, the culling rate ranging from 21 to 36% in dairy cows, being greater in USA than in EU and being dramatically affected by milk price (Mohd-Nor et al. 2014). The main involuntary culling reasons are reproductive failures and udder health issues, each comprising between a quarter and a third of total culling (Chiumia et al. 2013). Culling values are greater in larger and higher-yielding dairy cow farms (Hadley et al. 2006) and under low-forage diets regardless of the cow’s parity (Chiumia et al. 2013). Dairy buffaloes, sheep and goat have similar culling patterns but life span is usually longer in buffalo and sheep than in goats. There is considerable interaction between different characteristics. Dairy cows with subclinical ketosis are 20–50% less likely to become pregnant at first AI than normal cows (Walsh et al. 2007) and show greater lethargy and lying times (Itle et al. 2015). Similar effects have been reported in dairy goats (Zobel et al. 2015). There is also considerable variation between animals in what is ‘normal’. Take the example of oestrous duration, which varies between individuals, between breeds, according to production level and in response to nutrition and environmental factors. Oestrous is an example of a natural behaviour that makes management more difficult: most cows show standing oestrous behaviour from sunset to dawn, leading to the common practice of the ‘a.m.-p.m. rule’ (cows detected standing in the morning will be inseminated in the afternoon, and those detected in the evening will be inseminated the next morning). Values of fertility are low, the cumulative probability of conception between 20 and 145 DIM ranging from 0·5 to 46% in dairy cows (Madouasse et al. 2010) evidencing a large room for improvement. Technologies are not circadian! Furthermore, once one has invested in the technology the add-on costs of frequent use are minimal, meaning that repeated measurements can be made in each animal (at each milking, for instance) so that she can be tracked across time.

Welfare assessment of dairy animals is a hard and multi-disciplinary task, one that must take into account a number of objective measures but also a great many subjective ones. There is general agreement that animal welfare is assured when the 5 main freedom principles stated in 1979 by the UK’s Farm Animal Welfare Council (FAWC) are fulfilled. These freedoms (freedom from hunger and thirst, from discomfort, from pain, injury and disease, from fear and distress and freedom to express most normal behaviours) are internationally recognised, but they are ideal states rather than standards for acceptable welfare. Moreover, as pointed out by FAWC ‘there is no gold standard to measure good animal welfare’ (FAWC, 2014), considering that objective measures can be defined or recorded in some cases (e.g. lameness or injuries), but others are currently very difficult to assess (e.g. sadness, happiness, fear). Welfare Quality® was an EU FP6 research programme that developed semi-objective protocols for assessing farm animal welfare. For cattle (dairy, beef and veal calf) farms they identified 4 welfare principles (good feeding, good housing, good health and appropriate behaviour), 12 welfare criteria and 53 management practices (Forkman & Keeling, 2009). The definition of good health was absence of disease, injuries and pain, with physical, social and mental wellbeing assessed through four measures of appropriate behaviour. Two important principles of the Welfare Quality® approach should be recognised:

- the programme was fork to farm, i.e. lead by consumer expectations
- the protocols that emerged use animal based measures but are farm level assessments

The Welfare Quality® protocol has been adopted and is being used, farms being categorised as Excellent, Enhanced, Acceptable and Unclassified (unacceptable). The protocol is not without its critics; it is time consuming and costly and a small number of individual measures have a major impact on the classification and may thus become foci of effort to improve classification rather than actual animal wellbeing (De Vries et al. 2013). Our major concern is very simple: the approach does not provide the farmer with a toolbox for ongoing assessment of the
wellbeing of his cows, nor was it ever meant to do so. The questions that emerge are, does the farmer need such a thing, and can we provide it, either now or in the foreseeable future?

The DairyCare concept; individualised wellbeing through integrated action

Can technology provide data that is (a) animal-centric (relating to each individual cow) and (b) useful to the farmer? One individual brand of oestrous detection technology (an accelerometer placed in an ear tag) is reported to have sold 1.7 M items worldwide (Michaelis et al. 2014), and we can identify at least 11 other commercially available accelerometer technologies intended for oestrous detection (Table 1). The extent to which these technologies have been scientifically validated varies, but the main conclusion is quite clear: dairy farmers will pay for and use technologies that provide what is, to them, a straightforward answer to a straightforward question (should I inseminate cow x?) when they believe it will have positive economic impact. It is in that context that we should consider whether technology can assist dairy animal wellbeing.

Animal wellbeing is multifactorial, and one of the premises underlying the DairyCare project is that achieving the best solutions will require inputs from animal scientists, ethologists, veterinarians and agricultural engineers, working in partnership with small and medium sized enterprises (SME) and dairy equipment companies. The route to market identifies that this multidisciplinary cooperation will assist the development of technologies that are then integrated into best practice blueprints, which are then channelled through dairy consultancies to achieve better dairy animal welfare on farms that are more profitable as a result. DairyCare (COST Action FA1308) is a 4 year (March 2014 to March 2018) researcher network focused on dairy animal health and welfare which has as its main objective the improvement of dairy animal wellbeing through scientific and technological advance within the EU dairy industry (DairyCare, 2016). By enabling better wellbeing, DairyCare also aims to create positive societal impact from the ability to identify, traffic and milk individual animals, the first outcome (WG1). DairyCare includes agricultural engineers with knowledge of milking and management systems and computer scientists with knowledge of the design of algorithms for data extraction, analysis and interpretation. Through the combination of these skills, the biomarker and activity data will be used to construct future decision support systems that will assist farmers to optimise the wellbeing of their dairy animals, the third outcome (WG3). DairyCare supports a range of cross-disciplinary networking activities and uses a number of tools to achieve its objectives such as: open conferences for scientific debate around relevant topics, WG meetings for more focused debate in smaller groups about specific topics, Research Training Workshops (RTW) for providing training in relevant techniques for younger scientists, and Best Practice Workshops (BPW) to disseminate best practices to end-users. The DairyCare integrative concept is shown in Fig. 1, and Fig. 2 gives an overview of some of the specific topic-based activities that have already taken place or are scheduled. Proceedings from the three scientific conferences are published and available online (DairyCare, 2016):

- Health and welfare of dairy animals (held in Copenhagen in 2014)
- Lameness/Reproduction interface (held in Córdoba in 2015)
- Feeding behaviour as an indicator of health and welfare (held in Zadar in 2015)

Available technologies

Current management capabilities in the dairy sector include the ability to identify, traffic and milk individual animals,
<table>
<thead>
<tr>
<th>Objective</th>
<th>Manufacturer (address†)</th>
<th>Type &amp; features</th>
<th>Technology used</th>
<th>Reference link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Somatic cell count (SCC)</td>
<td>OCC, DeLaval (Tumba, SW)</td>
<td>Milk SCC by udder quarter</td>
<td>Analysis of cell ADN by u.v. fluorescence</td>
<td><a href="http://www.delaval.com/en/-/Product-Information1/Milking/Products/Statwork/VM-Station/DeLaval-online-cell-counter-OCC/">http://www.delaval.com/en/-/Product-Information1/Milking/Products/Statwork/VM-Station/DeLaval-online-cell-counter-OCC/</a></td>
</tr>
<tr>
<td>Activity behaviour (oestrous, feeding and health signs detection)</td>
<td>CowManager, SensOor, Agis Automatisering (Harmelen, NL)</td>
<td>Ear: activity, feeding, health</td>
<td>RF§, 3-axial accelerometer</td>
<td><a href="http://www.cowmanager.com/en-us/">http://www.cowmanager.com/en-us/</a></td>
</tr>
<tr>
<td></td>
<td>Cow Alert, IceRobotics (Edinburgh, Scotland, UK)</td>
<td>Leg: activity, oestrous, health</td>
<td>RF, 3-axial accelerometer</td>
<td><a href="http://www.icerobotics.com/products/">http://www.icerobotics.com/products/</a></td>
</tr>
<tr>
<td></td>
<td>CowScout, GEA (Düsseldorf, DE)</td>
<td>Neck or leg: activity, eating time, oestrous</td>
<td>RF, 3-axial accelerometer</td>
<td><a href="http://www.delaval.com/en/-/Product-Information1/Management/Systems/Activity-meter-system/">http://www.delaval.com/en/-/Product-Information1/Management/Systems/Activity-meter-system/</a></td>
</tr>
<tr>
<td></td>
<td>Silent Herdsmann Afimilk (Kibbutz Afikim, IL)</td>
<td>Neck or leg: activity, oestrous, rumination,</td>
<td>RF, 3-axial accelerometer</td>
<td><a href="http://www.afimilk.com/products/cow-monitoring/">http://www.afimilk.com/products/cow-monitoring/</a></td>
</tr>
<tr>
<td></td>
<td>MooMonitor, DairyMaster (Tralee, IE)</td>
<td>Neck: activity, oestrous, health</td>
<td>RF, 3-axial accelerometer, SMS¶</td>
<td><a href="http://www.dairymaster.com/heat-detection/">http://www.dairymaster.com/heat-detection/</a></td>
</tr>
<tr>
<td></td>
<td>Heatime, EFS (Westmeath, IE)</td>
<td>Neck: activity, oestrous, health</td>
<td>RF, 3-axial accelerometer</td>
<td><a href="http://www.efsltd.ie/">http://www.efsltd.ie/</a></td>
</tr>
<tr>
<td></td>
<td>RumiWatch, Itin+Hoch (Liestal, CH)</td>
<td>Nose and leg: activity, intake, drinking, rumination, lameness</td>
<td>RF and USB¶‡, 3-axial accelerometer, thermometer, pressure</td>
<td><a href="http://www.rumiwatch.ch/index.html">http://www.rumiwatch.ch/index.html</a></td>
</tr>
<tr>
<td>Mating alert</td>
<td>Celotor (Cali, CO)</td>
<td>Harness reader and tail inject</td>
<td>RF, SMS</td>
<td><a href="http://www.celotor.com/celotor/petes-y-operacion/">http://www.celotor.com/celotor/petes-y-operacion/</a></td>
</tr>
<tr>
<td>Calving alert</td>
<td>Vel’Phone, Medria (Châteaubourg, FR)</td>
<td>Vaginal temperature</td>
<td>Thermistor, SMS</td>
<td><a href="http://www.medria.fr/en_GB/products/vel-phone.html">http://www.medria.fr/en_GB/products/vel-phone.html</a></td>
</tr>
<tr>
<td></td>
<td>Moocall (Dublin, IE)</td>
<td>Tail ring</td>
<td>Accelerometer, SMS</td>
<td><a href="http://www.moocall.com/">http://www.moocall.com/</a></td>
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</table>
feed concentrates and total mixed rations fully automatically, and to obtain diagnostic data informing about several health and performance related criteria. A chosen set of the most important commercially available technologies currently in use for dairy cows is shown in Table 1 and Fig. 3.

**Identification was first**

An early evidence of the development of new technologies in the agricultural sector is the patent of Hanton & Leach (1974) on the first radiofrequency (RF) identification (ID) system of cattle using a glass encapsulated rumen bolus powered by a battery. The bolus was administered orally, retained in the reticulo-rumen, and its internal RF circuitry responded with a coded signal when interrogated by a stationary unit working at 75 MHz and placed at 3–5 m of distance. The current technological state-of-the-art in the livestock sector is centred on the individual animal, and most RFID transponders used today are inspired by Hanton & Leach’s original idea. RFID is heavily used in the dairy sector, and together with the fact that each lactating animal will regularly come to one specific point to be milked provides the basis of the individualistic management approach.

High performance RFID devices, allowing non-contact and fast dynamic reading, are a key priority for all engineered developments to be used under on-farm conditions. Current RFID of dairy cows is still based on large high-frequency transponders (i.e. neck collars) although miniaturised low-frequency devices of different ISO (International Organisation for Standardisation) technologies are cheaper and readily available (ear tags, injectable devices or rumen boluses). Interestingly, whilst RFID technology for cattle is an option for farmers in most EU countries (only Denmark has approved the generalised use of RFID in cattle), the current EU regulations compulsorily require the use of RFID in all small ruminants (breeding stock older than 6 months located in countries with more than 600 000 head) as the only way to trace and to build up credible animal inventories. Moving to compulsory RFID for cattle could help to accelerate the introduction and implementation of associated and new technologies (Caja et al. 2014). It should be pointed out that the RF needs are markedly different if intended for animal ID (low-frequency, 134.2 kHz) or for big data collection and transmission (high frequency, 13.56 MHz; very-high and ultra-high-frequency, 400–900 MHz), the reading of both RF variants being specific and the transceivers not inter-compatible. Moreover, ID transponders are usually passive (without battery) whereas data collectors and transmitters are active (with battery or their own source of energy). An animal with a missing, lost or non-readable transponder will be ‘invisible’ to the technology. As a result, when a sequential reading procedure is used (such as a line or rotary milking parlour, dynamic weighing scales) the ID of all animals behind the ‘not read’ will be mis-assigned, which must be avoided.

### Table 1. (Cont.)

<table>
<thead>
<tr>
<th>Objective</th>
<th>Manufacturer (address†)</th>
<th>Type &amp; features</th>
<th>Technology used</th>
<th>Reference link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rumen function</td>
<td>eCow Devon (Exeter, UK)</td>
<td>Rumen bolus: pH, temperature, drinking</td>
<td>RF, pH electrode, thermistor</td>
<td><a href="http://www.ecow.co.uk/">http://www.ecow.co.uk/</a></td>
</tr>
<tr>
<td></td>
<td>(Chateaubourg, FR)</td>
<td>Rumen bolus: pH, temperature</td>
<td>RF, pH electrode, thermistor</td>
<td><a href="http://www.wellcow.co.uk/bolus/">http://www.wellcow.co.uk/bolus/</a></td>
</tr>
<tr>
<td>Integrated functions</td>
<td>SmaXtec Sensor, SmaXtec Animal Care (Graz, AT)</td>
<td>Rumen bolus: activity, temperature, drinking, oestrous</td>
<td>GPS, RF, temperature sensor, 2-axial accelerometer</td>
<td><a href="http://www.lotek.com/wildcell.htm">http://www.lotek.com/wildcell.htm</a></td>
</tr>
<tr>
<td>Position</td>
<td>WildCell, Lotek (Ontario, CA)</td>
<td>Neck</td>
<td>GPS, RF</td>
<td><a href="http://www.cattle-watch.com/">http://www.cattle-watch.com/</a></td>
</tr>
<tr>
<td>location</td>
<td>CattleWatch (Rehovot, IL)</td>
<td>Neck</td>
<td>RF, mesh network indoors (200–400 m)</td>
<td><a href="http://www.omnisense.co.uk/agriculture.html">http://www.omnisense.co.uk/agriculture.html</a></td>
</tr>
</tbody>
</table>

†Officially assigned country codes: ISO 3166–1 alpha-2 codes
‡Radio frequency (ultrahigh frequency)
¶Mobil-to-mobil short message service
‡‡Universal serial bus connection
Using TICs for dairy wellbeing

The implementation of TIC and especially the recent concepts of SNO (smart networked objects) and IoT (internet of things), opened a new era of communication in which things, not only humans or animals, are the main users of local communication wireless networks and internet. This is communication anytime, anywhere, by anyone and anything, providing ‘things’ with an individual identity and virtual ‘personality’ which operates in smart spaces using intelligent interfaces to create new values (AIC, 2010). In practice the creation of so called M2M (machine to machine) real-time or near-real-time connectivity is also necessary. All ‘things’ need to be embedded with microelectronics,
sensors and software, that let them connect, exchange data with a central operator and be able to communicate, either directly with a network, internet or with internet-connected devices. In fact, ‘things’ in the IoT and ‘machines’ in M2M, are physical entities whose identity, state (or the state of their surroundings) are capable of being relayed to an internet-connected TIC infrastructure.

The implementation of TICs in the livestock industry, and lately the use of SNO and IoT, lead to the new concept of PLF (precision livestock farming) which aims to automatically monitor individual animals for optimising their production process. According to Berckmans (2008), PLF consists of measuring variables, modelling the data to select information, and then using these models in real-time for monitoring and controlling the animals. Originally intended for application in agronomy, we consider that the use of the ‘precision’ term in livestock is not fully expressing the needs of FAWC’s freedoms required in animals and PLF should be used jointly with the concept of ‘good practice’. The main variables that might be monitored by PLF are the use of key livestock resources (feed, water, land surface), performances (milk yield, weight), health (for instance coughing, body temperature, lameness), behaviour (activity, rumination, fighting) and environment (temperature, humidity, air speed, toxic gases). PLF is a technological response to the loss of contact between husbandry staff and animals, as a result of larger more automated farms, providing accurate information to reduce dependency on human labour and informing decision making. PLF has many possibilities of use with regard to wellbeing in the dairy industry, either for intensive large-dairy farms or extensive (Bocquier et al. 2014). Many TIC companies stand to benefit from this new world of opportunities, including mobile network operators and fixed broadband providers, system integrators, cloud service providers, mobile App developers, sensor and wireless infrastructure vendors, and purveyors of big data infrastructure and analysis.

Another concept introduced by the TIC industry is that of ‘wearable’ devices such as smart watches or smartglasses (in humans) and, in the SNO and IoT context, they are devices connected to RF networks or internet, respectively. As we have seen, cows have their own wearable devices (Fig. 3), which complement the RFID devices and are intended to monitor what the cow is doing and provide early detection of health or behavioural problems. With this purpose, most wearable devices are equipped with sensors. Rutten et al. (2013) categorised the available sensors to support health management on cow dairy farms and schematised the framework that describes the steps followed from a sensor to a decision.

**Non-wearable devices**

Automated milking systems (AMS) in dairy cows are a good example of how non-wearable TICs can be integrated with automation (robotic arms) to help dairy husbandry staff by reducing routine workload and freeing-up time for management tasks, which are simultaneously assisted by automatic and real-time data collection (the latter can happen in conventional milking parlours as well). Once the RFID has

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**Fig. 3.** Location of engineered devices for in situ data collection in a cow: (1) ear tag, (2) halter, (3) neck collar with counterweight, (4) reticulo-rumen bolus (in reticulum), (5) rear leg pedometer, (6) upper tail ring, (7) tailhead inject, and (8) vaginal bolus.
provided the identity, milk flowmeters, milk conducti-
meters, infrared or laser assisted video cameras collect
data that are then integrated in computers by specific
‘smart’ software using complex algorithms previously vali-
dated with assumed gold standards, usually derived from
observational data. Data are abundant, so let us examine
the outcomes (Table 1).

Technologies are available for recording of body weight
and of food intake using automated electronic scales
which were developed in the EU and involve SMEs and
larger enterprises from EU and other COST countries
(including Switzerland and Israel). Imaging technologies are
also available, such as 3D imaging for body condition
scoring (‘DeLaval BCS’; Krukowski, 2009) and infrared
thermography for exploring udder health, although this
last is currently questioned (Castro-Costa et al. 2014).
Force sensors are being used in gait consistency analysis
for lameness detection (‘StepMetrix’ and ‘Gaitwise’).

Milk composition can provide information about nutrition,
metabolic state and health through changes in major (Sutton
& Morant, 1989) and minor milk components (Larsen et al.
2016). Milk sampling has the major advantage of being
non-invasive and automatable, and the combination of
routine sampling and the generalised use of MIR (mid-infra-
red) spectrometry in dairy herd improvement programs
focused on ‘simple’ protein, fat and lactose composition
also now allows the simultaneous detection of more inform-
ative biomarkers such as ketone bodies and individual fatty
acids (De Marchi et al. 2014). An application example is
the use of fatty acids profile for predicting methane emission
(van Gastelen & Dijkstra, 2016).

A number of integrated in-line/real time milk analysis
technologies are available. Afimilk’s ‘AfiLab’ system
(Leitner et al. 2012) is able to measure the major milk com-
ponents (i.e. fat, protein and lactose) and milk coagulation
properties by near-infrared analysis (NIR), and can be com-
bined with the ‘Online Cell Counter’ for somatic cell count
(SCC) based on the analysis of cell’s ADN by u.v. fluores-
cence (Albrechtsen et al. 2011). Lattec’s ‘Herd Navigator’
focuses on milk biomarkers for the detection of oestrus
(progesterone analysis), subclinical and acute mastitis
(lactate dehydrogenase analysis) and ketosis (β-hydroxybuty-
rate analysis, BHB). The Herd Navigator system automatic-
ally selects the cow to sample, at which milking session
it should be monitored and which variables should be mea-
sured. New robotic collection and analysis of biological
samples (e.g. milk, saliva, sweat and hair), including the
use of metabolomics and proteomics, are under develop-
ment to obtain data of metabolic disorders and wellbeing-
related biomarkers which could be applied not only in
cows but also in sheep, goats and others.

Wearable devices

Activity sensors (Table 1 and Fig. 3) are wearable devices
that are now used very commonly in dairy herds. Most
reproductive management technologies (e.g. oestrus,
mating, calving) are based on activity-recording of one
sort or another using tri-axial accelerometers (‘SensOor’,
‘Cow Alert’, ‘CowScout’, ‘Qwes’, ‘Activity meter’, ‘Silent
‘HeatSeeker’ and ‘RumiWatch’). They are offered to wear
as an ear tag (Bikker et al. 2014), nose halter, neck collar
or leg (preferably rear) pedometer. Some accelerometers
also offer information on feeding behaviour (e.g. eating, ru-
minating, drinking). Special case is the ‘MooMonitor’ which
is using pressure sensors for detecting the standing behav-
ior of dairy cows during oestrus.

Simpler devices for heat and mating activity detection use
RFID transceivers attached to a harness for bulls or andro-
genised cows (‘Celotor’). Cows are identified with an inject-
able transponder in the tailhead which is read by the
transceiver at mounting.

Calving detection is monitored by changes in tail position
with devices attached to the tailhead containing acceler-
ometers (‘Moocall’) or by the dramatic change of tempera-
ture of a vaginal device using thermistors when it is
expelled during labour (‘Vel’Phone’ and ‘iVET’).

Reticulo-rumen boluses (‘eCow’, ‘WellCow’, ‘smaXtec
pH’) assess rumen function by specific sensors (e.g. tem-
perature, pH, pressure) which might be related to rumen
pH for SARA (subacute rumen acidosis) detection and
with feeding and drinking behaviour. Additionally, data pro-
vided by an integrated tri-axial accelerometer offers informa-
tion on reproductive activity, feeding and locomotion for
integrated farm management decisions, including lameness
detection (‘smaXtec Sensor’: smaXtec, 2016). A simpler
case is the ‘San’Phone’ only equipped with thermistors
informing about rumen temperature and drinking bouts.

Additionally, position location is offered by GPS devices,
in some cases associated with 2 or 3 axial-accelerometers
and thermistors (‘WildCell’, ‘CattleWatch’ and ‘Ser. 500
Cluster Geolocation System’), usually used in extensive live-
stock or wild animals under on-field conditions.

All of these technologies are capable of identifying live-
stock requiring attention or ‘at risk’ and communicating
with dairy farm staff at any time using M2M communication
by App and SMS telephone messages. We have identified
technologies that are commercially available, recognising at
the same time that others will exist at various stages of exper-
imental development. It would not be appropriate to comment
on the usefulness or otherwise of the individual commercial
technologies, since the claims made for accuracy, precision,
false positives and negatives are in most cases those of the
manufacturer and have not been tested independently. We
do, however, offer the following observations:

- Although manufacturers often claim to offer ‘complete
  solutions’, no one system individually offers everything
  that could be achieved by using a full combination of
  all systems operating together
- Almost without exception, the different technologies
  operate ‘stand alone’, and will not communicate with
  each other
The future

The term ‘psychedelic cowbell road’ has nothing to do with cows, it is a name coined to describe the dashboard display of a popular make of electric car when driven in autopilot mode. If driverless cars are to work (and many manufacturers are determined that they will) technology needs to provide two things:

- a continuous and detailed 360 degree assessment of the car’s environment that can detect every object and determine what that object is likely to do in the foreseeable future
- algorithms that will ensure that the car makes the appropriate, safe response to the data provided

Surprisingly, one of the technology companies that has already successfully introduced driverless vehicles is a spin-out comprising a small handful of college students (Varden Labs, 2016). If technology can give us 360 degree imagery moving at high speed in variable lighting conditions, it should certainly be able to provide a detailed picture of a stationary dairy unit, and if that basic technology can be built by ‘college kids’ it need not be inherently expensive. Driverless technology is most unlikely to find application in Formula One motor racing. That degree of precision would be almost impossible to achieve, but equally, that application is not needed. So, let us examine what is needed for wellbeing management.

The objective is to assist good husbandry, not replace it. The basis of the assistance is to identify which cows amongst very many are most in need of specialist attention on a particular day, and to provide information (and potentially biological samples) that would help to inform the care given to those cows. Do we need ‘precision’? If the objective is to use technology on an intermittent basis to categorise individual animals within a herd as either enjoying wellbeing or not, then a significant degree of precision becomes necessary, as does a gold standard for them to fall either side of. As mentioned previously, that gold standard does not exist (FAWC, 2014). What does exist is the assessment that we could have made of that same cow yesterday, the day before, last week and so on, together with knowledge of her physiological state, genetic background and production parameters. What we are looking for is evidence of change, change that places her outside the currently desirable characteristics and therefore categorises her as ‘at risk’. We also have the same information for her herdmates, and we have data relating to her environment, so if the same change is evident at the same time in many animals, the risk is something different, not related to our cow of interest but to the herd as a whole. The driverless car is not trying to constantly maintain a precise and defined distance from the kerb, it is aiming to be somewhere in ‘safe territory’. The skilled herdsman with years of experience cannot necessarily say that a particular cow has specific problem x, but they can know that there is something not right that requires further intention; they can place her inside or outside ‘safe territory’.

The deliverable must be as simple as possible. Farmers are most unlikely to use ‘systems’ that require them to cross reference between several different pieces of information coming from different sources, and if they did decide to do so, they would be at high risk of not making the correct decision or not being able to make a decision at all. Long before driverless cars, traffic lights provided straightforward information that made a driver’s decision easy. Exactly the same needs to be delivered by our wellbeing technology; the green cows in the main group are needing routine management, the amber cows are ones that the technologies are now paying special attention to and the red cows in the holding pen are the ones that the farmer and their vet need to look at now.

Who will deliver this assistance, and to whom? It is evident from Table 1 that there is no shortage of potentially useful technologies, but what is lacking is the skilled herdsman who reduces the information to a simple answer for themselves or their boss (one can be reasonably sure that it will often be a ‘boss’, i.e. the manager of a large unit of some sort). Most probably in future business models the technology will be ‘owned’ by service providers who will be contracted to place it on farm, receive data from it, interrogate, integrate and analyse that data and then respond with the traffic light message, or simply an automatic move of shedding gates from one position to another. Who will be the customers? ‘Big farms’ is far too simplistic an answer, for some of the big farms of the future might slowly become big by accident rather than specific design, whereas others might be planned big from the bottom up. The wellbeing monitoring system might have rather different requirements, almost ‘rescue’ based in the first instance but cost-benefit proven in the second. The third and arguably most important ‘big farm’ would not be a single farm at all, but a cluster of smaller farms that gather together to dilute investment and overhead costs and then share data in order to maximise the impact of the technology. There are other players too: the immediate response will necessarily involve veterinary professionals, either employed or contracted by the farm or the service provider. Medium term responses will involve dairy consultants, feed advisers and breeding companies, and in the longer term the service provider will share data with national breeding programmes to maximise genetic progress towards improved wellbeing traits.

How will the data integration be achieved? The proprietary problems associated with combining multiple data-streams are already reduced in the business model, nevertheless, integrating numerous datasets is always challenging. In all probability, major strands of future research will include:

- Establishment of minimum effective datasets
- Creation of multiple-output sensors
- Exploitation of multiple endpoints from single datasets

A possible but nevertheless highly speculative model is shown in Fig. 4. This ‘Third Sense’ approach envisages a
multi-output sensor in the rumen (here called the Third Ear, in the sense of inner ear) measuring temperature (which also enables determination of water intake), feed intake, rumen motility, activity, balance, heart rate and pH. Some of these measures already exist (see above), whilst others will need to be developed. Imagine a single ‘red flag’ raised by the Third Ear in an individual cow that was previously healthy. She is now amber status, and the system deploys the Third Eye and for the next few hours the cow is followed everywhere by a drone that closely monitors her behavioural interactions with other cows and her environment. Sometime later the Third Hand robotic arm reports that a milk sample has returned positive for a metabolic problem and simultaneously the drone reports aberrant behaviour. The cow moves to red status, and next time she leaves the milking unit she is diverted to a holding area for examination. The examining vet will have immediate access to the cow, her data and to samples of, for instance, saliva, interstitial fluid or sweat taken by the Third Hand. This is a ‘progressive integration’ model which, from an algorithmic point of view, is likely to be relatively simple to model. If numerous red flags have been raised simultaneously the progression would be different; the cow would move immediately to red status and this time the Third Eye would be deployed emitting attractive aromas that she would follow to a holding and sampling area, to ensure that she is seen as rapidly as possible. This model is one of a number that could be proposed; a Third Nose might be monitoring the cow’s emissions, for instance. We use the term Third Sense not only to suggest that a small number of sensor streams may be optimal, but also to indicate that it is a third party (us!) who is receiving the information.

Optimistic pipeline, or pie in the sky? Before you decide, remember that Rank Xerox abandoned their own invention, the personal computer, believing it to have no future! The incentive to develop wellbeing technologies for the dairy sector is huge, and could also spawn the development of related technologies for other animal sectors, as well as in human medicine for application in the very young and in elderly dementia sufferers. As a final thought (literally) the drones that were envisaged as a Third Eye can, in theory at least, be controlled by humans simply by thought process (LaFleur et al. 2013). Emotions can be used to fly the drone upwards (happy thoughts) or downwards (sad thoughts). If technology can tap into human thoughts in this way, perhaps knowledge of the cow’s mood is actually closer than we might think.

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