© 2022 Universities Federation for Animal Welfare
The Old School, Brewhouse Hill, Wheathampstead,
Hertfordshire AL4 8AN, UK
www.ufaw.org.uk

Animal Welfare 2022, 31: 373-385
ISSN 0962-7286
doi: 10.7120/09627286.31.4.006

Electric shock control of farmed animals: Welfare review and ethical critique

D Grumett[*†] *and A Butterworth*[‡]

[†] University of Edinburgh, New College, Mound Place, Edinburgh EH1 2LX, UK
[‡] WelfareMax and Animal Welfare Training Ltd, 14 Stonewell Lane, Congresbury, Bristol BS49 5DL, UK
* Contact for correspondence: david.grumett@ed.ac.uk

Abstract

The available methods of electric shock control or containment of farmed animals are increasing and potentially include: (i) fixed and movable electric fencing; (ii) cattle trainers; (iii) prods or goads; (iv) wires in poultry barns; (v) dairy collecting yard backing gates; (vi) automated milking systems (milking robots); and (vii) collars linked to virtual fencing and containment systems. Since any electric shock is likely to cause a farmed animal pain, any such control or containment must, to be ethically justifiable, bring clear welfare benefits that cannot be practicably delivered in other ways. Associated areas of welfare concern with ethical implications include the displacement of stockpersons by technology, poor facility design, stray voltage, coercive behavioural change and indirect impacts on human society and values.

Keywords: *animal welfare, automated milking system, collar, electric fencing, electric shock, ethics*

Introduction

When electricity is used on farms to transmit power to generate outputs such as light, heat or motion, a basic safety expectation is that animals are protected from current by appropriate distancing or insulation. If a current of sufficiently high energy passes through an animal, its negative welfare effects may include pain (here, pain is used to include what is sometimes termed discomfort), distress, injury or death. These negative effects may be intentionally harnessed and developed for control and containment purposes.

Over the past ninety years, the uses of electricity to control and contain farmed animals by aversive stimulation have gradually increased, with successive new applications being found. Intentionally causing animals pain is ethically problematic because the experience of pain is intrinsically bad (Tannanbaum 1999). This is the earliest modern grounding of animal ethics and is supported by the argument that if causing humans unnecessary pain is ethically unjustifiable, causing sentient animals unnecessary pain is also ethically unjustifiable (Grumett 2018). Where such animals are under direct human control, including in farming contexts, the ethical requirement not to cause them unnecessary pain is even greater because humans are responsible for them. In some states this is legally codified (eg Animal Welfare Act 2006; 9[2][e]) and enforceable.

This article will address electric shock control applications in which animals subjected to control retain consciousness and retain the capacity for voluntary bodily movement. Other potential uses include stunning, which is used to render an animal unconscious and therefore insensate to pain prior to slaughter, and immobilisation, which has sometimes been used to prevent voluntary muscular movement while mutilations such as castration or dehorning are performed. Stunning and immobilisation fall outside the scope of this paper.

The objectives of this paper are to provide an overview of the different forms of electric shock control potentially used on farmed animals, to identify their welfare implications and to offer ethical assessment of these. As part of the research for this paper we have conducted a comprehensive survey of manufacturer specifications for energisers available for online purchase. The anonymised dataset resulting from this survey can be seen online in Appendix 1 in Supplementary Material. The first section of the paper will review potential control and containment applications, which include: (i) fixed and movable electric fencing; (ii) cattle trainers; (iii) prods or goads; (iv) wires in poultry barns; (v) dairy collecting yard backing gates; (vi) automated milking systems (milking robots); and (vii) collars linked to virtual fencing and containment systems. In the second section, the ethical implications of each of these uses of electricity on animals will be considered in turn. It will be shown that, while some applications may potentially bring welfare benefits in particular situations, because they all have certain negative welfare impacts, they require ethical evaluation. The third section will offer an overall

Table 1 Energiser specifications by species.

Species	Minimum		Maximum		Average		Sample size
	Energy (J)	Voltage (V)	Energy (J)	Voltage (V)	Energy (J)	Voltage (V)	
Cattle	0.07	5,000	25	16,800	4.23	9,779	128
Sheep	0.07	6,900	20	16,800	4.83	9,995	85
Goats	0.07	6,900	20	16,800	3.93	10,058	82
Pig	0.12	7,000	18.5	16,800	3.42	10,350	45
Poultry	0.20	7,900	5.0	13,000	1.77	9,663	26

ethical assessment of the electric shock control of farmed animals, extending to issues such as the displacement of stockpersons by technology, facilities' design, discretionary versus rational control, stray voltage, behavioural change and indirect effects on human society and values.

Overview of applications

Fixed and movable electric fencing

Electric fencing was developed during the 1930s in the United States and then in New Zealand. In Wisconsin, Edwin Gengler (1934) created an electrically charged stock enclosure and patented it. Early fences were sometimes powered by home generators or mains supply. Due to the high current, these were more dangerous than fences supplied by batteries. By the later 1930s, electric fencing was in use across the United States to protect farmed animals from predatory wild animals such as bears and racoons, and to keep wild animals including antelope, buffalo, deer and elk off crops (McAtee 1939). In New Zealand, later in the same decade, William Gallagher developed electric fencing, apparently after connecting his car to a generator so that if a horse rocked the car, it would receive an electric shock (Goldsmith 2013). Following installation and use on his own farm, Gallagher gained his first patent in 1939, by which time he was marketing his device to neighbours.

Conventional electrical fencing was further developed during the 1960s as a cheaper alternative to traditional wooden fencing, requiring fewer materials and reduced set-up time and labour (McKillop & Sibly 1988). Electric fencing delivers either a pulsed direct current or an alternating current to an animal that touches one of two or more horizontal wires running between wooden or metal posts fixed in the ground. This causes the animal to experience pain and, in response, to move away. The number, height and spacing of wires used typically varies according to species. The wire spacing varies according to the animal size, with small animals requiring narrower spacing. As an animal usually touches only one wire at a time, the number of wires used for each species is less critical than their spacing and height, which constitute the physical fenced barrier (Kubik 2014). Typically, 1–3 wires are sufficient for cattle, 3–4 for pigs, 4–6 for sheep and goats and nine for chickens (Rutland Electric Fencing [UK] undated). Energisers are usually identified as suitable for one or more species. The energy ranges (joules) and voltage (volts) provided for energisers with published species and energy specifications are shown in Table 1.

The table is based on a comprehensive survey of manufacturer specifications for energisers available for online purchase from any country and all energisers for which data were presented were included. Details are provided in the accompanying anonymised dataset in Appendix 1. (Note: Five energisers specified for poultry were excluded from the poultry comparison because the high energy levels delivered suggest that they would be used to protect birds from predators rather than for containment purposes).

The wide range of parameters is due to diverse practical considerations related both to external factors and to species. The actual current that may flow to an animal varies according to the resistance of the hair, skin, body tissues and electrical circuit (McKillop *et al* 2003), which includes wires and any leakage of current to earth through wet insulators or vegetation in contact with the fence wire. Dew, rain, moist soil and wet animals are all likely to increase conductivity and thus the current delivered (Campbell *et al* 1956). However, vegetation in contact with the fence is likely to result in energy loss as the fence 'shorts' through the vegetation to the ground, reducing the potential difference (voltage) of the circuit (ibid). In general, the greater the length of the fence, and the closer to vegetation that the conducting wires are, the greater the likelihood of variation in the current delivered. Moreover, the energy levels given in specifications are maximal that might be attained under ideal conditions: in real situations the actual current and energy delivered will probably be lower than the maximum possible and, for the reasons just discussed, will be variable.

The high upper-end energies for cattle may be required to control large breeds with hairy coats, and cows with calves, which will overcome significant barriers to protect or retrieve a calf (Lalman *et al* 2010). Goats are normally curious and are likely to investigate and test a fence regularly, especially by attempting to push under it (Hart 2001). Pig skin is mostly hairless and is exposed, and pigs are likely to touch a fence with their nose, which is a sensitive body part (Kubik 2014).

If sheep have thick wool, this is likely to limit conductivity (Cholewińska *et al* 2019) which, in combination with insulating hoof material (collagen), is likely to result in poor return of the electrical pulse. In poultry, feathers, scaly legs and feet have poor conductivity (also due to collagen), which is also likely to result in poor return of the electrical pulse (Ashokkumar & Ajayan 2021). The thickness of an animal's hair, wool or feathers (Tesfaye *et al* 2018) is a further variable according to breed, season and management practices. With cattle, electric fencing may, like a traditional fence, be used as a 'creep', with wires fixed high enough to allow calves to pass under but low enough to impede the passage of adults (Miles 1951). This allows calves to remain with their dams but also permits them to access additional pasture unavailable to their dams or to any mature bulls running with the dams, promoting weaning and a degree of independence within the herd.

From the 1990s, portable electric fencing has been in use (Morgan 2016). This consists of stainless steel wire woven into plastic mesh strips that attach to plastic posts that are pushed into the ground by hand. The fence is usually powered by a portable solar or battery energiser unit. Portable systems may be quickly transported, erected, dismantled and moved to manage animal access to land for grazing and other purposes, including temporary or seasonal hazards.

Cattle trainers

In cow sheds, the cubicles or stalls in which cattle are housed are designed so that faeces and urine produced by an animal drop into the channel or passage that runs the length of the barn behind the cubicles or stalls. (This is often called the scraper passage, because it is lower than the cubicle beds and is scraped by a tractor or track-based automated scraper to remove manure). However, a standing animal may sometimes defaecate or urinate into the rear part of the lying area and bedding within the cubicle or stall, rather than into the passage further back. Waste may then accumulate on the hind feet, legs, hindquarters or udders of the animal, increasing the risk of disease. From a welfare perspective, cubicles need to have sufficient depth to allow for forward lunging on rising, which is a normal species behaviour (Dirksen *et al* 2020). Waste accumulation may be an increased problem where this welfare need is met.

Cattle trainers were developed to encourage cattle to deposit their waste in the channel running behind the cubicle. A trainer is a retractable and height-adjustable electrified rod passing across the stall about one-third of the way from the front and just above the animal's shoulders (Hultgren 1991). When an animal is preparing to expel faeces or urine, it typically arches its back. If it does so whilst standing forward in the cubicle or stall, it receives an electric shock. However, if the animal steps backwards to avoid being shocked, its position results in the waste being deposited into the channel. Due to differences in size and body movement between individuals, trainers need adjusting for each individual if they are to be effective. This means that, whenever an animal returns to a different stall, the trainer in that stall may need repositioning. Following adjustment, the trainer needs to be firmly secured to avoid any possibility of it falling onto an animal's back. A range of energisers marketed as usable with cattle trainers are specified as 2.5–8.0 kV and 0.02–0.09 J. However, a published advice source states that they should not exceed 2.5 kV (Midwest Rural Energy Council 2005).

Prods or goads

A cattle prod or goad is a narrow, battery-powered rod of widely varying length held by a stockperson at one end and with two electrodes at the other, which shock an animal touched by them. Although some manufacturers suggest that these 'coax' an animal, goading means provoking or annoying in order to stimulate an action or reaction (Pearsall 1998). The prod produces a short-duration shock aimed at causing pain and a consequent movement response in an animal. When the prod is activated, an alarm may sound, primarily for operator safety (Robinson *et al* 1990). Prods are designed for use by stockpersons to encourage animals to move, or to continue moving, during operations such as walking to and from the milking parlour and loading into or unloading from transportation such as for market or prior to slaughter. In situations such as these, if a prod is at hand, a stockperson may decide to use it. A comprehensive survey of prods available for online purchase identified 13 for which specified voltage was available (see Appendix 1). These voltages were in the range 3.8–5.0 kV. The large majority were at the top of this range, as indicated by the mean average voltage of 4.9 kV. Application of a prod is likely to produce significant pain, especially in sensitive body locations, as evidenced by aversive behavioural responses such as leg lifting, kicking and swaying and by increased heart rate (Lefcourt *et al* 1985, 1986).

Wires in poultry barns

Within open barn poultry housing, single-strand electrified wires may be used in several areas to influence bird location, nesting and behaviour. First, for laying hens and broiler breeders in barn systems, wires may be set up to influence where eggs are laid. 'Floor eggs' are those laid in barns outside of the designated nesting area or nesting boxes, typically around the edges of housing where the wall provides some similar protection. These eggs are at increased risk of contamination and moisture and require greater labour to collect. By installing an electrified wire around the barn perimeter, the farmer may stop young hens forming the habit of laying in this zone (Vroegindeweij *et al* 2014). Such a wire may also help reduce the frequency of one or more hens smothering another in corners. Use of an electrified wire for this purpose is seen in The Netherlands, Germany and France.

A second use of electrified wires is egg protection. In either caged or open laying systems, laid eggs roll down from the laying area into the egg conveyor running in front (Hartung *et al* 2009). In some countries, wires may be fixed along the front of the nesting box to deter birds from leaning forwards to peck the eggs that have rolled down and are passing in front of them. A third use of wires in some countries, in barns housing either laying hens or broilers, is to prevent hens sitting on feeder and water lines (Appleby 1984) and soiling the feeder pans and drinkers and their surrounding area. To do this, a wire may be run immediately above the feeder and water lines. Our survey of commercially available energisers (see Appendix 1) was unable to identify any energisers specified for electrifying wires inside poultry barns. Where such wires are in place it is likely that a lower voltage multi-species fence energiser will be used.

Dairy collecting yard backing gates

In the area outside a milking parlour entrance, where cows are gathered prior to milking, a long, slow-moving motorised backing (or crowding) gate may be in use. This system is sometimes known as an 'electric dog.' It encourages animals to enter the parlour by gradually reducing the size of the waiting area. This eliminates the need to chase or handle animals in the collecting yard, which would be likely to cause them stress. The metal gate runs the width of the concrete yard and is mounted on tracks that run along either the yard floor, the top of the wall enclosing the sides of the yard or on girders above the yard. A single milker can operate the gate while supervising milking without needing to leave the milking pit, although a herdsman is still likely to be required to round up stragglers (Paranhos da Costa & Broom 2001). This system increases milking efficiency and reduces milk contamination risks resulting from dirt being brought into the parlour by the milker and transferred to equipment. The gate sometimes has a scraper attached and so may also be used to clean the yard. When the gate is activated, a bell or buzzer precedes forward movement. The successive auditory and visual cues alert animals to the movement. However, some gates may include an energised wire running along their length, which will shock any animal that touches them. The energisers used are of the same types as those used for short, low-current electric fences, although they are typically powered from the mains to avoid the need to replace or recharge batteries. Since animals that are stressed or in pain may be difficult to milk, the energisers used are likely to be low power. A rare, published advice source states that, like cattle trainers, they must never exceed 2.5 kV (Midwest Rural Energy Council 2005). However, in our comprehensive survey of energisers available for online purchase (see Appendix 1), the only energiser found that was explicitly identified as suitable for use in backing gates was specified as 7.5 kV/0.3 J.

Automated milking systems (milking robots)

Milking robots were first commercialised in The Netherlands. Since the early 1990s they have been most widely used there and in Denmark, Sweden and Iceland, although have also become common in Norway, Belgium, Switzerland and Canada (Eastwood & Renwick 2020). There is some usage elsewhere, including Germany and the UK. Animals entering the machine are individually identifiable by means of a microchipped ear tag, a transponder in a rumen bolus (a sensor that is swallowed and remains in the animal's rumen or reticulum) or a transponder contained in a collar. Cows may approach the machine for milking when they wish and may be encouraged by a food incentive. They may also be automatically prevented from entering if they have recently been fed, or sufficiently milked. Following entry, a robotic arm detects the teats and cleans them, attaches the cluster unit, milks the animal, detaches the cluster unit and washes it. The machine measures the quantity of milk delivered and may also analyse its composition to monitor both product quality and individual cow health. If, following milking, the cow fails to leave the unit promptly (eg within 20 s: Wenzel *et al* 2003), an electric shock is administered by a 'tickler' to make her do so. A tickler is a wire rope hanging down above the cow and touching her back. The energy and power delivered are not included in published specifications and in some systems this feature may be deactivated (Schewe & Stuart 2015).

Collars linked to virtual fencing and containment systems

Virtual fencing was first developed in the United States for the purpose of companion animal confinement (Anderson 2007). Equipment for use with livestock was first manufactured in 1987, although full virtual fencing systems only became commercially available in 2017. There are currently four significant providers worldwide. In Australia, Agersens marketed the eShepherd brand for cattle and Halter did so in New Zealand. The Norwegian company NoFence began to sell collars for sheep and goats, and then for cattle, on the European market. In the United States, Vence has launched a cattle system.

From a technological viewpoint, virtual fencing systems are a logical development of the movable electric fencing described in *Fixed and movable electric fencing*. Whereas a traditional fence is either fixed in position or requires a farmworker to move it, a virtual fencing system is intended to keep animals within a potentially shifting demarcated area. The animal wears a neck collar that emits a signal captured by global positioning system satellite technology and allows its position, and sometimes body surface temperature, to be recorded. Via a software application, a moveable virtual boundary is programmed into the system's geographic information system. When an animal approaches this boundary an audio cue is emitted to encourage it to move away. If an animal persists towards the boundary, or through it, this is followed by an electric shock delivered to the top of the neck (Anderson *et al* 2003). One provider specifies the audio cue as 82 dB and the shock as 0.2 J and 1 s duration for cattle (NoFence Grazing Technology undated [a]) and 0.1 J and 0.5 s duration for sheep and goats (NoFence Grazing Technology undated [b]). Others do not publish these specifications.

An advantage of virtual fencing over traditional electric or other physical fencing is that, because the system registers the direction of animal movement towards and across the boundary, it may permit any escaped animal to return into the containment zone unimpeded, whereas animals that break through traditional fencing are typically stranded until returned to the enclosure by a farmworker. Moreover, the NoFence specifications state that no animal will be automatically shocked. A shock will not be applied if an animal moves very slowly or very quickly, because such movement may indicate injury or flight from harm. Neither will an animal be shocked if it has already received a specified number of shocks within a defined time-period.

Virtual fencing may be used, in principle, for a range of purposes. These include the elimination of poaching (the churning of wet ground by cattle and subsequent solidification as an uneven hard surface) and the protection of animals from non-lethal hazards. However, because of the significant initial investment required and ongoing running costs, the most likely use on-farm is as part of a precision grazing system for beef or, most commonly, for dairy cattle grazing. Stocking density and fresh pasture access may be remotely controlled, and if the pasture height, quality and composition are measured or predicted by other methods (eg assumptions based on rainfall, temperature and daylength), virtual fencing may form part of a sophisticated intensive grazing system (Verdon *et al* 2021a).

Virtual fencing is also increasingly used in free-ranging settings, including in conservation grazing contexts (Morgan-Davies 2015). In these locations, conventional fencing may be impractical due to the high cost of the fence length required, or because of difficulties accessing remote locations. Animals nevertheless need containing for their own safety, road safety and to prevent them grazing crops or rare plant species (Umstatter 2011) or polluting water courses. Nevertheless, because virtual fencing works by modifying behaviour, which is not entirely predictable, it cannot reliably deliver containment in situations where it is highly important for safety reasons that animals do not access an area (Anderson *et al* 2003), such as adjacent to a busy highway or high-speed railway line.

Electronic collars may also be used to help manage breeding, such as by influencing mating preference in paddocks where males and females run together (Lee *et al* 2008). However, we consider that they would be unlikely to provide an effective means of gender segregation for breeding control purposes as an electric shock is unlikely to deter males in heat from seeking mating opportunities.

Ethical analysis

A summary of ethical issues by electric shock control method can be seen in Table 2.

Fixed and movable electric fencing

From a containment perspective, the purpose of a hedge or traditional fence is to establish a physical barrier through which the farmed animals being contained are unable to pass. An electric fence, in contrast, while also visible, is usually in itself an ineffective physical barrier, able to be walked over or through, or pushed under, by animals unless it is live (McDonald *et al* 1981). In order to serve as an effective boundary, an electric fence causes pain and is designed to do so. This is a significant welfare issue. Indeed, in some publicity descriptions, these are stated operating objectives. Terms such as 'punching', 'packing a punch', 'kicking', 'jolting' and 'zapping' are among those used to describe functioning, suggesting that shock by a larger current is preferable to shock by a smaller current regardless of the level of pain caused to an animal. However, from an ethical perspective, animals under human control should, as far as is practicable, be kept free from pain (Grumett 2018). This ethical principle is a legal requirement in some jurisdictions. For example, in the United Kingdom, it is an offence for a person to fail to take reasonable steps to avoid or reduce the suffering of an animal for which they are responsible (Animal Welfare Act 2006). The ethical principle suggests that the current delivered in a shock should be only as high as is needed to contain the animal. As discussed in *Fixed and movable electric fencing* in the *Overview of applications*, regulation of the current is, in practice, difficult due to environmental and operating contingencies. For example, even if the fence area is well maintained, such as by being kept clear of vegetation, to ensure that the fence operates effectively in worst-case conditions an energy level will be required that may be unnecessarily high for typical conditions. In practice, it is unlikely that the energiser output will be adjusted to allow for such contingencies. Contained animals that are shocked will therefore sometimes experience levels of pain that are above those required for the purpose of containment on that occasion.

Moderate pain of limited duration may be ethically justified if necessary to enable a greater harm to be avoided. However, in situations in which a boundary is protecting an animal from potential harm, the harm is likely to be sufficiently great to justify traditional fixed fencing. Such harms might include a steep incline, falling debris, deep water, a busy highway or a fast railway line. Since a fixed electric fence may occasionally lose power or be broken through by a herd member, its use cannot be ethically justified in instances where failure may result in severe injury or death to animals or humans.

In other instances, a movable electric fence may protect animals from lower-level harms, such as grazing or browsing harmful flora or accessing waterlogged ground and becoming lagged in mud. (Environmental factors may be ethically significant, although will only fall within a farm animal ethics assessment in so far as environmental protection or degradation impact on farm animal welfare). However, it needs to be considered whether the pain that results from shocking is proportionate to the potential harm being avoided, and if the harm could be avoided in other ways, such as by moving animals to other land, improving drainage or taking steps to eradicate potentially harmful flora. Moreover, as discussed in *Collars linked to virtual fencing and containment systems* in the *Overview of applications*, domesticated animals, if afforded sufficient individual and group learning opportunities, have the ability to avoid some lower-level harms.

Cattle trainers

As described in *Cattle trainers* under *Overview of applications*, cattle trainers are designed to preserve the physical hygiene and comfort of the bovine animal in the stall which, if delivered, is a welfare benefit. However, clear evidence is lacking that cattle controlled by trainers are any cleaner than those that are not, and the use of trainers sometimes disrupts normal lying behaviour as animals seek to avoid being

Table 2 Summary of ethical issues by electric shock control method.

Electric shock control method	Ethical issues
Fixed and movable electric fencing	Current and pain level cannot be closely regulated
	Cannot protect from serious harms
	Lesser harms may be removable by other means
Cattle trainers	Lack of clear welfare benefits
	Direct negative health and comfort impacts
	Indirect negative behavioural impacts via stray voltage
Prods or goads	No welfare benefits
	Acute stress
	Perceived need to use suggests poor facilities design and/or poor management
Wires in poultry barns	Perceived need to use suggests poor accommodation design
	Indirect negative health and behavioural impacts via stray voltage
Dairy collecting yard backing gates	Lack of welfare benefits
	Disruption of herd behaviour
	Cow choice inhibited
	Most likely to shock cows already in pain
Automated milking systems (milking robots)	Cows coerced into abnormal behaviour
	Presented as voluntary but are not
Collars linked to virtual fencing and containment systems	Benefits unevenly distributed among group members
	Different current levels cannot be applied to individuals according to associative learning needs
	Incomplete understanding of potential impacts on animal health and behaviour

shocked (Hultgren 1991). In a large Swedish study of over 15,000 animals, the incidence and seriousness of several serious health conditions was higher among animals controlled by trainers than in animals housed without them. Rates of silent heat, clinical mastitis and ketosis increased, silent heat changed from a neutral disease to a major culling risk and reproductive performance fell (Oltenacu *et al* 1998). The lack of clear benefits combined with likely negative health and comfort impacts suggests that the use of trainers is ethically unjustifiable.

Moreover, trainers can contribute to the wider welfare problem of 'stray voltage' by creating an electric field that induces a potential difference across equipment with metallic parts running in parallel to the trainer lines, such as water lines and milk pipelines (Appleman & Gustafson 1985). As farms become larger and more mechanised, stray voltage problems are likely to increase, especially where financial challenges discourage equipment maintenance and replacement. On dairy farms, signs and symptoms of stray voltage include periodic and unexplained falls in production, slower or incomplete milking, increased incidence of mastitis, nervousness and reluctance to use water bowls or metallic feeders (ibid). Stray voltage has been found to induce increased cattle activity (Rigalma *et al* 2010). A meta-analysis of 22 studies has indicated that behavioural responses can occur with currents as low as 3 mA (Erdreich *et al* 2009). The risk that trainers will contribute to the negative health and comfort impacts caused by stray voltage is a second reason why they are ethically unjustifiable.

Prods or goads

In research on beef cattle, acute stress was found to be induced by the pre-slaughter use of electric prodders (Warner *et al* 2007). Among pigs, repeated shocking immediately prior to stunning and slaughter has been shown to increase levels of the stress indicators epinephrine and magnesium in blood plasma (D'Souza *et al* 1998). In another study, which replicated potential normal practice, pigs loaded and unloaded for transport to the abattoir with the use of prods exhibited significantly increased levels of cortisol and lactose in their blood plasma, which also indicated stress (Ludtke *et al* 2010). The use of electric prods is likely to cause animals avoidable suffering with no welfare benefit and is therefore ethically unjustifiable under the conditions described.

On-farm, the movement operations described in *Prods and goads* in the *Overview of applications*, are likely to be stressful for animals. Stress at loading or during movement is recognised as occurring when handling races are poorly designed (eg straight rather than curved), or when animals are allowed to see movement through the race, pen or loading ramp fence rather than these having high solid sides to give a sense of containment, or if animals experience shadows, contrasting light and dark areas, reflections or loud or high-pitched noise (Grandin 1997). Prods or goads are sometimes used repeatedly on animals that are unable to move easily away, such as a tightly bunched group in a pen or race, in order to break up the group. Loading and unloading situations that require animals to walk up or down a sloping ramp are also likely to be stressful (ibid). Animals in these situations are less likely to co-operate and the response of the farmworker moving them may be to shock them using a prod. The availability and use of prods is likely to be an indicator of poor facility design and poor management. For this reason, the responsibility for their use does not lie solely with the farm workers directly dealing with the animals. The designers and owners of facilities have an ethical duty to operate facilities in which the distress experienced by animals during necessary handling operations is minimised. They should not add to this by placing farmworkers in a situation where, in order to move animals, they need to deploy external aversive stimuli in response to behaviours resulting from distress.

Wires in poultry barns

Electrified wires impede the normal behaviour of perching and limit the ability of birds to exercise choice over their location. Within a given barn configuration their use may reduce the risk of harm to birds resulting from smothering and from contamination by soiling of the feed and water lines, and so may be viewed as ethically justified in order to prevent a greater harm. However, a more strategic and more ethically justifiable way to reduce these problems would be to design accommodation that promotes normal behaviour by taking account of nesting preferences (Lentfer *et al* 2013). Although hens nest gregariously, especially at younger ages, they may prefer boundary locations because these provide some enclosure and are easier to locate than boxes in the centre of a barn (Riber 2010). Increasing space allowances, allowing outdoor access for exploration and perching, and expanding opportunities to exercise choice may each also contribute to reducing or eliminating the need for electrified wires by extending opportunities to exercise normal behaviours.

A poultry barn is likely to contain a variety of metal building materials, housing and equipment. These increase the risk of harm to birds due to stray voltage resulting from both electrified wires and other electrical equipment such as heating and lighting. Stray voltage is likely to be exacerbated by moisture, which may be at high levels in winter (Halvorson *et al* 1989). As described in *Wires in poultry barns* in the *Overview of applications*, electrified wires may be installed in order to influence bird location. However, when hens choose to avoid nesting areas and lay floor eggs, this may be in an attempt to avoid stray voltage in the nesting area (Worley & Wilson 2000). The use of electrified wires to prevent perimeter nesting is, in turn, likely to increase stray voltage levels and the incidence of smothering, which typically occurs at barn perimeters and in corners. For at least some voltage types, stray voltage may lead to increased mortality, reduced feed and water intake, hyperexcitability and reduced fertility (Halvorson *et al* 1989; Vidali *et al* 1996). Although stray voltage may be reduced and even eliminated by ongoing monitoring, investigation and maintenance, electrified wires increase the risk of stray voltage and these associated welfare problems. As with trainers, the risk that poultry barn wires will contribute to the negative health and comfort impacts caused by stray voltage is a second reason why they are ethically unjustifiable.

Dairy collecting yard backing gates

As described in *Dairy collecting yard backing gates* in the *Overview of applications*, a backing (or crowding) gate enables cows to be directed into the milking parlour by a milker working inside the parlour by encouraging them to move as a group, which is part of their normal behaviour, towards the parlour and into it. Moving cows to and from the parlour once, twice or sometimes three times per day can be labour-intensive, and an automated gate eliminates the need for a herdsman to be routinely stationed in the collecting yard to manage animal movement. However, when cattle are electrically shocked, they display agitation by hoof lifting, muscle contraction, sudden jerks, shoulder shaking, mouth opening and arching the back (Reinemann *et al* 1999). Any such agitation is likely to reduce the efficiency of the milking process as well as being an indicator of pain and distress. Electrified backing gates can therefore only be ethically justified if any agitation that they cause is necessary for avoiding greater negative welfare impacts. No such benefits are apparent.

The development of automated backing gates to gather cows for milking has had the effect of reducing the frequency of use for this purpose of electric prods, which have been observed to lengthen the training period duration for new milkers (Albright *et al* 1992). However, the tradition of electric shock control in the collecting yard exercised by an individual herdsman has probably contributed to its ethical acceptance in some quarters as one of the functions of backing gates. The electrification of these automated gates makes them no longer a simple physical barrier but adds the function of producing, or potentially producing, an aversive stimulus in animals. However, although parlour entry order is generally consistent within a herd, it is influenced by both milking side choice and health. Individuals with a strong milking side preference are likely to prefer to enter a herringbone configuration on one side rather than the other (Paranhos da Costa & Broom 2001). A crowding system in which individuals may be discouraged or prevented from waiting their turn or moving to their preferred side of the yard is therefore likely to inhibit the normal behaviour of individuals and herd synchrony and is therefore ethically questionable. Moreover, animals with sub-clinical mastitis, reduced locomotion due to lameness or other pain, which might be exacerbated by milking, are likely to retreat to the end of the milking order (Polikarpus *et al* 2015) and so be more frequently subject to any electric shock control function of a backing gate. However, these individuals are likely to require careful and humane handling and stockperson attention.

Automated milking systems (milking robots)

In early research into automated milking, it was recognised that the time cows lingered following automated milking, and the frequent need for a herdsman to move them on, were potential barriers to commercialisation. In one project, the average voluntary exit time from the milking system was 3.3 min, although this ranged from 6 s up to, for the oldest cow, over 16 min (Winter & Hillerton 1995). The average wait time of 3.3 min was 30% of the average 11 min total visit time per cow. Another early study simply reported that, following milking, 38% of cows remained in the milker and had to be pushed out (Metz-Stefanowska *et al* 1992). It is likely that cows require physical recovery time following the intensive process of automated milking; indeed, the full reversion of teats to their normal dimensions takes several hours (Stádník *et al* 2010). Inherent in automated milking systems (AMS) is therefore a trade-off between cow exercise of normal behaviour, which from a welfare perspective should be promoted, and maximising the rate of milking by an expensive machine for commercial reasons.

An electric tickler is a means of coercion designed to move animals out of an automated milker quickly (Stuart *et al* 2013). As described in *Automated milking systems (milking robots)* in the *Overview of applications*, very little time is allowed for the animal to move out of the milker before the device activates. Due to this, any animal that chooses to remain in the milker will receive an electric shock (Bear & Holloway 2014). However, an animal may be prevented from leaving the milker by crowding outside or by an individual dominant animal. In any case, automated milking requires a large change to normal group synchrony. Whereas in traditional milking systems, cows will move, be milked and feed as a group, within AMS animals move, are milked and receive their feed reward following milking individually. A tickler is part of a system that coerces cows into behaviour that is abnormal for them at both individual and group levels and its use is therefore ethically questionable.

The behaviour of cows that have been electrically shocked suggests that they experience pain. One experiment investigating the likely effects of shocks at milking showed that, at lower currents, animals shocked bi-weekly became tense and displayed limited movement. As the current increased, so did agitation. The experiment was terminated due to the extreme behavioural responses presented by some individuals, which at 10 and 12.5 mA included back arching, pawing the ground and jumping (Lefcourt *et al* 1986). An alternative means of encouraging animals to exit an automated milker may be an air puff (Holloway *et al* 2014). AMS are frequently presented in positive terms as 'voluntary' and as delivering cow freedom (Driessen & Heutinck 2015). If these claims were true, a cow would be permitted to remain in the milker for an extended period before stockperson investigation of her unwillingness to move, and perhaps for as long as she wished. From an ethical perspective, there is a concerning gap between the highly positive claims made for AMS and the reality of the actual or potential automated coercion on which they depend.

Collars linked to virtual fencing and containment systems

Following the long research and development phase described in *Collars linked to virtual fencing and containment systems* in the *Overview of applications*, and recent commercialisation, significant claims are currently being made for virtual fencing and containment systems. One overview states that such systems have the "potential to revolutionise management of the livestock industries", with benefits including "reduced labour, improved herd management, and protection of environmentally sensitive areas" (Campbell *et al* 2019). Moreover, it is affirmed that, in commercialisation, animal welfare is a "priority consideration." An advantage of virtual fencing systems over traditional electric fencing is that virtual systems shock a known individual on a particular body part with a measurable current. This avoids the problem discussed in *Fixed and movable electric fencing* in the *Overview of applications*, that a traditional electric fence will deliver a current that varies according to uncontrollable external factors, the breed and condition of the animal and the body location of the shock. Virtual fencing is therefore better able to satisfy the ethical requirement that the pain experienced by the shocked animal is no greater than that required to deliver the welfare benefit. (Because a virtual fence-line can be breached it should never be relied upon in situations where this may result in mortality or serious injury to the contained animal. A shock level sufficiently high to deliver injury or extreme pain is therefore not justifiable on the grounds that it protects an animal from even worse injury, pain or death).

The ability of animals to learn a virtual system, especially when visual cues are absent, has been extensively discussed. The removal of all visual cues is likely to be problematic for learning (McSweeney *et al* 2020), and therefore ethically problematic. With virtual fencing, when the boundary is moved there is no visual cue. However, if cows are unable to see that a physical object causing an aversive stimulus has been removed, they are normally significantly more likely to avoid a location where they have previously experienced such stimulus, even if this entails walking a greater distance to access food (ibid). In one experiment it took four days for cattle to re-adjust after virtual fencing was deactivated, in contrast to reportedly 'no time' following the removal of physical electric fencing (Markus *et al* 2014). However, in a precision grazing system, a boundary may be moved daily or even several times a day.

It may be argued that the audio cue resolves ethical issues by reducing the likelihood that an animal will experience the pain resulting from subsequent shocking (Lee *et al*

2009). Moreover, a cumulative learning effect has been observed, with herd members hearing the audio cues of closely adjacent conspecifics and thereby heeding the virtual boundary without themselves interacting with it (Campbell *et al* 2017). When a goat herd is first introduced to virtual fencing, group learning probably also increases (Keshavarzi *et al* 2020). Virtual fencing may therefore be viewed as promoting herd socialisation, which is part of normal behaviour. However, among cattle, wide variation in learning speeds between individuals has been noted. These depend on a range of factors, such as temperament, early environment and socialisation (Campbell *et al* 2018). Slow learners will receive more shocks than fast learners. In one virtual fencing experiment involving 12 dairy cows, three animals received, on average, more than three electrical shocks per day (3.3, 4.0 and 6.3) whereas others were subjected to an average of just one (Lomax *et al* 2019). The animals receiving the greatest number of shocks also experienced many more of the audio cues that preceded the shock (between 8.7 and 35.8). Within virtual fencing systems, some animals thus experience a disproportionately high number of shocks, meaning that the penalties for any benefits that virtual fencing might deliver to each group member equally (eg improved grazing management) are unevenly distributed among members. This is ethically problematic because some animals will gain the benefit for little or no penalty, while for others the benefit may be offset to a large extent by the ongoing penalties experienced.

At its best, virtual fencing promotes associative learning, identifying and rewarding behavioural change (eg stopping, turning or backing-up) rather than simple location. However, for associative learning to be more effective, systems need to apply different current levels to individuals depending on their subjective response to being shocked, which may range from ear movement through vocalisation to pressing forward or running (Lee *et al* 2007). Systems at this level of sophistication, although ethically desirable, are currently unavailable and may be commercially unviable.

It may not always be necessary to control all herd members directly. Partial direct control may have some use in promoting mob grazing or keeping groups together on common land. Given the significant financial investment that virtual fencing requires, partial control may be viewed as delivering insufficient benefit. Yet with sheep, directly controlling two-thirds of a flock has been found to be equally effective in regulating location as directly controlling the whole flock (Marini *et al* 2020). However, this is in the context of virtual fencing being difficult to operate for sheep, especially those with young, with high escape levels having been observed (Brunberg *et al* 2015, 2017). When dominant cattle herd members are directly controlled with collars and other members that are not directly controlled follow them, these other cattle may benefit from any resulting gains without experiencing the pain of any electric shocks. This synchrony is potentially possible because cows are herd animals that are gregarious and live in structured groups (Correll *et al* 2008). Goat herds exhibit similar synchronicity (Fay *et al* 1989). Such partial direct control, when it delivers the required degree of containment, is ethically beneficial because it is likely to reduce the total number of shocks experienced by a herd and slow learners may be exempted from direct control. Even so, although partial direct control brings some welfare benefits, it is problematic in situations where a duty of care needs to be exercised over all individuals in order to protect from harm (eg keeping them off a railway track or busy highway).

Some important welfare implications of virtual fencing are unclear and require further research. Dairy cattle that are virtually fenced for more than about four days may display reduced activity, grazing time and ruminating time and experience increased stress (indicated by milk cortisol levels) (Verdon *et al* 2021b). It might be possible to replace the electrical shock that a collar delivers to the top of the neck with a tactile stimulus produced by a vibrating motor (Acosta *et al* 2020). However, it is unclear at present how effective this would be in controlling the movement of all individuals in a herd, nor if it would reduce or eliminate welfare concerns. At present, a precautionary principle is justified that permits commercial development in the context of ongoing research to understand and limit potential negative impacts on health and behaviour.

Overall ethical assessment

In any situation where welfare may be compromised, the primary ethical concern needs to be the immediate pain caused to the animal. Turning first to fencing, a well-constructed physical barrier of appropriate height and materials can contain animals as well as, or better than, fixed, movable or virtual electric fencing, even though such a barrier may well be more difficult and more costly to construct. In a situation where electric (including virtual) fencing is being considered, one or more probable welfare benefit(s) to animals that could not practicably be delivered by a physical barrier would need to be identified to justify the likely pain caused. The settings to which this applies include conservation grazing, where ecological considerations may be stronger than welfare.

Prods and goads, and electrified wires in poultry barns, are likely to be resorted to where there is sub-optimal facility design. Poorly configured races, pens, ramps and housing may produce management and welfare problems to which electric shock control is a short-term response that adds another serious welfare issue. A far more appropriate response would be to reassess and re-design facilities so that the factors leading to movement or location challenges are reduced or eliminated.

Dairy collecting yard backing gates and ticklers in automated milking systems are striking instances of the evolution of electric shock control technology. Whereas a prod or goad might previously have been applied as a result of stockperson decision, the electric shock is now mechanically caused. From a welfare perspective this is an ambiguous development. The application of a shock by a mechanism, perhaps according to a rational algorithm, may be viewed as preferable to similar application by a human. This is because mechanistic or algorithmic operation eliminates the possibility of the intentional mistreatment of individual animals by a gratuitous stockperson, such as by frequently shocking the same individuals or by shocking body parts that are highly sensitive to pain. However, the distancing of the stockperson from the animals that these technologies encourage leads to a reliance on electric shock control, or the prospect of it, and its normalisation. In many situations, what is needed, and what is far preferable to either discretionary or automated shocking, is intervention by a caring and competent stockperson. Cows at the end of the milking line and those that are reluctant to exit a milker may well require compassionate human attention.

In cattle and poultry barns, the use of trainers and electrified wires may, in combination with other electrical equipment, sub-optimal configuration and poor maintenance, contribute to stray voltage and the welfare problems associated with it. This shows that, especially indoors, the potential welfare impact of any electrical shock equipment needs to be considered in the context of all the electrical equipment installed, used and maintained in a facility.

The use of automated milking system ticklers requires animals to change their normal behaviours for the farmed setting quickly and significantly if they are to avoid repeated electric shocks. Automated milking systems require cows to exit the milker many times more quickly than if the system was truly voluntary. The normal behaviour of resting in a standing position immediately once milking is completed, which includes the early period of teat recovery, is thus severely restricted for the purely commercial reason of maximising milk yield per machine. Animals face a choice between having standstill time and avoiding electric shocks.

In addition to the pain that electric shocking is likely to cause an animal, the changing relationship with humans, to which electric shock control technologies have contributed, also needs to be evaluated. Over a period of about ninety years, the development, commercialisation and use of the electric shock technologies surveyed in this paper have contributed to a shift away from the direct human control of farmed animals to automated control methods that are becoming increasing sophisticated. With good reason, automated control is sometimes viewed as replacing interaction with humans, such as in the description of virtual fencing as an 'electronic shepherd' (Campbell *et al* 2019; Langworthy *et al* 2021). It reduces the reasons for stockperson interaction with animals and therefore limits the opportunities for identifying welfare issues that automated monitoring may not detect.

As humans are also animals it is appropriate to end with brief reflection on the current impacts of the imagined and actual electric shock control of animals on society. Surveying some available technologies, Whiting (2016) presents a continuum between the control of animals and humans. At the group level, cattle prods and goads may be used against crowds that are easily depicted in animalised terms as requiring herding, corralling and containing (Scotton 2019), as well as against individuals in contexts of political and other criminal torture (Hillman 2003). Cattle prods and goads are thus used to control both human and non-human animals in a context of ongoing technology transfer. Another important instance, this time of imaginative creation for use against animals and humans but then subsequent development and deployment principally for use against humans, is a TASER (Tom A Swift Electric Rifle). In the science fiction novel by Victor Appleton (1911), from which its real-life inventor Jack Cover took its name, a TASER was deployed by American ivory hunters while hunting elephants in Africa to immobilise both wildlife and native persons. This weapon, which is essentially a highly portable energiser, shoots two electrode darts attached to copper wires across several metres between the operator and the victim. During travel the darts diverge, and as they approach and penetrate the victim's body at least 10 cm apart an electrical circuit is completed and the victim is immobilised by the pulsed DC current. Dangers include high risk of injury resulting from falling onto a hard surface, especially in the urban locations where TASERs are typically deployed by law enforcement personnel, because the immobilised individual is unable to extend their arms to brace against the fall. Electric shock control technologies conceived, developed and used on animals are thus readily on hand for use on groups of humans that may be 'animalised' on such grounds as ethnicity, religion or migration status. This is partly a matter of the simple availability of equipment and knowledge of its use, but also the result of a social acceptance of the use, and potential use, of such technologies for control purposes.

This ethical analysis has shown several reasons for serious concern regarding the development and use of electric shock control technologies on animals. Instances of these technologies being used to control humans provide further reasons to reduce and replace their use on animals.

Animal welfare implications

There is currently a high level of tolerance in animal agriculture for diverse methods of electric shock control. Since these cause pain to animals, they should only be employed if necessary, and to the level required, to avoid greater pain or suffering to animals. By reducing the use of electric shock controls on animals by replacing them with alternative control methods, welfare is likely to be improved. Cattle trainers, prods or goads, electrified wires in poultry barns and electrified backing gates in dairy collecting yards are unlikely to be justifiable on these grounds and have been shown to cause welfare problems. Fixed and moveable electric fencing is likely to be justifiable in some situations if its welfare purpose is clear and its operation carefully managed. The ticklers in automated milking systems and collars linked to virtual fencing and containment systems require further welfare assessment because they coerce animals into rapid changes in their normal behaviours and modes of learning.

Declaration of interest

AB and DG are members of the Animal Welfare Committee, Defra, UK.

Acknowledgements

DG was co-investigator on an AHRC research grant to Prof David Clough (University of Aberdeen). AB was a consultant on this grant.

References

Acosta N, Barreto N, Caitano P, Marichal R, Pedemonte M and Oreggioni J 2020 Research platform for cattle virtual fences. *Proceedings 2020 IEEE International Conference on Industrial Technology* pp 797-802. IEEE: Piscataway NJ, USA. https://doi.org/10.1109/ICIT45562.2020.9067313

Albright JL, Cennamo AR and Wisniewski EW 1992 Voluntary entrance into the milking parlour. In: Ipema AH, Lippus AC, Metz JHM and Rossing W (eds) *Prospects for Automatic Milking* pp 459-465. Pudoc Scientific Publishers: Wageningen, The Netherlands. https://doi.org/10.1016/0301-6226(93)90080-2

Anderson DM 2007 Virtual fencing-past, present and future. *The Rangeland Journal 29*: 65-78. https://doi.org/10.1071/RJ06036

Anderson DM, Hale CS, Libeau R and Nolen B 2003 Managing stocking density in real-time. In: Allsopp N, Palmer AR, Milton SJ, Kirkman KP, Kerley GIH, Hurt CR and Brown CJ (eds) *Proceedings of the VIIth International Rangelands Congress* pp 840-843. 26th July - 1st August 2003, Durban, South Africa

Animal Welfare Act (UK) 2006 *Animal Welfare Act 2006*. https://www.legislation.gov.uk/ukpga/2006/45

Appleby MC 1984 Factors affecting floor laying by domestic hens: a review. *World's Poultry Science Journal 40*: 241-249. https://doi.org/10.1079/WPS19840019

Appleman RD and Gustafson RJ 1985 Source of stray voltage and effect on cow health and performance. *Journal of Dairy Science 68*: 1554-1567. https://doi.org/10.3168/jds.S0022-0302(85)80994-2

Appleton V 1911 *Tom Swift and His Electric Rifle; or, Daring Adventures in Elephant Land*. Grosset: New York, USA

Ashokkumar M and Ajayan PM 2021 Materials science perspective of multifunctional materials derived from collagen. *International Materials Reviews 66/3*: 160-187. https://doi.org/10.1080/09506608.2020.1750807

Bear C and Holloway L 2019 Beyond resistance: geographies of divergent more-than-human conduct in robotic milking. *Geoforum 104*: 212-221. https://doi.org/10.1016/j.geoforum.2019.04.030

Brunberg, EI, Bergslid IK, Bøe KE and Sørheim KM 2017 The ability of ewes with lambs to learn a virtual fencing system. *Animal 11*: 2045-2050. https://doi.org/10.1017/S1751731117000891

Brunberg EI, Bøe KE and Sørheim KM 2015 Testing a new virtual fencing system on sheep. *Acta Agriculturae Scandinavica, Section A - Animal Science 65*: 168-175. https://doi.org/10.1080/09064702.2015.1128478

Campbell DLM, Lea JM, Farrer WJ, Haynes SJ and Lee C 2017 Tech-savvy beef cattle? how heifers respond to moving virtual fence lines. *Animals 7(9)*: 72. https://doi.org/10.3390/ani7090072

Campbell DLM, Lea JM, Haynes SJ, Farrer WJ, Leigh-Lancaster CJ and Lee C 2018 Virtual fencing of cattle using an automated collar in a feed attractant trial. *Applied Animal Behaviour Science 200*: 71-77. https://doi.org/10.1016/j.applanim.2017.12.002

Campbell DLM, Lea JM, Keshavarzi H and Lee C 2019 Virtual fencing is comparable to electric tape fencing for cattle behavior and welfare. *Frontiers in Veterinary Science 6*: 445. https://doi.org/10.3389/fvets.2019.00445

Campbell LE, Mowry GR and Hartstock JG 1956 *Factors affecting efficiency of electric fence operation.* Agricultural Research Service 42. United States Department of Agriculture, USA

Cholewińska P, Iwaszkiewicz M, Łuczycka D, Wysoczański T, Nowakowski P, Czyż K, Wyrostek A and Bodkowski R 2019 Electrical characteristics based on resistance and impedance of Polish Olkuska sheep lambs wool. *Journal of Natural Fibers 17*: 1366-1377. https://doi.org/10.1080/15440478.2019.1568347

Correll N, Schwager M and Rus D 2008 Social control of herd animals by integration of artificially controlled congeners. In: Asada M, Hallam JCY, Meyer J-A and Tani J (eds) *International Conference on Simulation of Adaptive Behavior: From Animals to Animals* pp 437-446. Springer: Berlin, Germany. https://doi.org/10.1007/978-3-540-69134-1_43

Dirksen N, Gygax L, Traulsen I, Wechsler B and Burla J-B 2020 Body size in relation to cubicle dimensions affects lying behavior and joint lesions in dairy cows. *Journal of Dairy Science 103*: 9407-9417. https://doi.org/10.3168/jds.2019-16464

Driessen C and Heutinck LFM 2015 Cows desiring to be milked? milking robots and the co-evolution of ethics and technology on Dutch dairy farms. *Agriculture and Human Values 32*: 3-20. https://doi.org/10.1007/s10460-014-9515-5

D'Souza DN, Warner RD, Leury BJ and Dunshea FR 1998 The effect of dietary magnesium aspartate supplementation on pork quality. *Journal of Animal Science 76*: 104-109. https://doi.org/10.2527/1998.761104x

Eastwood CR and Renwick A 2020 Innovation uncertainty impacts the adoption of smarter farming approaches. *Frontiers in Sustainable Food Systems 4*: 24. https://doi.org/10.3389/fsufs.2020.00024

Erdreich LS, Alexander DD, Wagner ME and Reinemann D 2009 Meta-analysis of stray voltage on dairy cattle. *Journal of Dairy Science 92*: 5951-5963. https://doi.org/10.3168/jds.2008-1979

Fay PK, McElligott VT and Havstad KM 1989 Containment of free-ranging goats using pulsed-radio-wave-activated shock collars. *Applied Animal Behaviour Science 23*: 165-171. https://doi.org/10.1016/0168-1591(89)90016-6

Gengler E 1934 *Stock enclosure and system of electrically charging the same. US Patent no 1976721A*. https://patents.google.com/patent/US1976721A/en

Goldsmith P 2013 *Legend: From Electric Fences to Global Success: The Sir William Gallagher Story*. Random House: Auckland, New Zealand

Grandin T 1997 The design and construction of facilities for handling cattle. *Livestock Production Science 49*: 103-119. https://doi.org/10.1016/S0301-6226(97)00008-0

Grumett D 2018 Ethics, religion and farm animal welfare. In: Amos N and Sullivan R (eds) *The Business of Farm Animal Welfare* pp 32-44. Routledge: UK. https://doi.org/10.9774/gleaf.9781351270045_4

Halvorson DA, Noll SL, Bergeland ME, Cloud HA and Pursley R 1989 The effects of stray voltage on turkey poults. *Avian Diseases 33*: 582-585. https://doi.org/10.2307/1591125

Hart SP 2001 Recent perspectives in using goats for vegetation management in the USA. *Journal of Dairy Science 84(S)*: E170-E176. https://doi.org/10.3168/jds.S0022-0302(01)70212-3

Hartung J, Briese A and Springorum AC 2009 Laying hens in aviaries: development, legal and hygienic aspects. In: Aland A and Madec F (eds) *Sustainable Animal Production: The Challenges and Potential Developments for Professional Farming* pp 315-328. Wageningen Academic Publishers: Wageningen, The Netherlands

Hillman H 2003 Electrical devices used by prison officers, police and security forces. *Medicine, Conflict and Survival 19*: 197-204. https://doi.org/10.1080/13623690308409691

Holloway L, Bear C and Wilkinson K 2014 Re-capturing bovine life: robot-cow relationships, freedom and control in dairy farming. *Journal of Rural Studies 33*: 131-140. https://doi.org/10.1016/j.jrurstud.2013.01.006

Hultgren J 1991 A preliminary study of behavioural methods for assessing the influence of electric cow-trainers on animal health. *Veterinary Research Communications 15*: 291-300. https://doi.org/10.1007/BF00430034

Keshavarzi H, Lee C, Lea JM and Campbell DLM 2020 Virtual fence responses are socially facilitated in beef cattle. *Frontiers in Veterinary Science 7*: 711. https://doi.org/10.3389/fvets.2020.543158

Kubik R 2014 *Farm Fences and Gates: Build and Repair Fences to Keep Livestock In and Pests Out.* Voyageur: Minneapolis MN, USA

Lalman D, Gill D, Highfill G, Wallace J, Barnes K, Strasia C and LeValley B 2010 *Nutrition and management considerations for preconditioning home raised beef calves.* Oklahoma State University Division of Agricultural Sciences and Natural Resources, USA

Langworthy AD, Verdon M, Freeman MJ, Corkrey R, Hills JL and Rawnsley RP 2021 Virtual fencing technology to intensively graze lactating dairy cattle. I: Technology efficacy and pasture utilization. *Journal of Dairy Science 104*: 7071-7083. https://doi.org/10.3168/jds.2020-19796

Lee C, Henshall JM, Wark TJ, Crossman CC, Reed MT, Brewer HG, O'Grady J and Fisher AD 2009 Associative learning by cattle to enable effective and ethical virtual fences. *Applied Animal Behaviour Science 119*: 15-22. https://doi.org/10.1016/j.applanim.2009.03.010

Lee C, Prayaga K, Reed M and Henshall J 2007 Methods of training cattle to avoid a location using electrical cues. *Applied Animal Behaviour Science 108*: 229-238. https://doi.org/10.1016/j.applanim.2006.12.003

Lee C, Prayaga KC, Fisher AD and Henshall JM 2008 Behavioral aspects of electronic bull separation and mate allocation in multiple-sire mating paddocks. *Journal of Animal Science 86*: 1690-1696. https://doi.org/10.2527/jas.2007-0647

Lefcourt AM, Akers RM, Miller RH and Weinland B 1985 Effects of intermittent electrical shock on responses related to milk ejection. *Journal of Dairy Science 68*: 391-401. https://doi.org/10.3168/jds.S0022-0302(85)80837-7

Lefcourt AM, Kahl S and Akers RM 1986 Correlation of indices of stress with intensity of electrical shock for cows. *Journal of Dairy Science 69*: 833-842. https://doi.org/10.3168/jds.S0022-0302(86)80473-8

Lentfer TL, Gebhardt-Henrich SG, Fröhlich EKF and von Borell E 2013 Nest use is influenced by the positions of nests and drinkers in aviaries. *Poultry Science 92*: 1433-1442. https://doi.org/10.3382/ps.2012-02718

Lomax S, Colusso P and Clark CEF 2019 Does virtual fencing work for grazing dairy cattle? *Animals 9*: 429. https://doi.org/10.3390/ani9070429

Ludtke CB, Silveira ETF, Bertoloni W, de Andrade JC, Buzelli ML, Bessa LR and Soares GJD 2010 Bem-estar e qualidade de carne de suínos submetidos a diferentes técnicas de manejo pré-abate. *Revista Brasileira de Saude e Producao Animal 11*: 231-241. [Title translation: Welfare and meat quality of pigs submitted to different pre-slaughter handling techniques]

McAtee WL 1939 The electric fence in wildlife management. *The Journal of Wildlife Management 3(1)*: 1-13. https://doi.org/10.2307/3796387

McDonald CL, Beilharz RG and McCutchan J 1981 How cattle respond to electric fences. *Journal of the Department of Agriculture, Western Australia, Series 4(22)*: 99-101

McKillop IG, Pepper HW, Butt R and Poole DW 2003 *Electric Fence Reference Manual, Research and Development Surveillance Report 607*. DEFRA: London, UK

McKillop IG and Sibly RM 1988 Animal behaviour at electric fences and the implications for management. *Mammal Review 18*: 91-103. https://doi.org/10.1111/j.1365-2907.1988.tb00078.x

McSweeney D, O'Brien B, Coughlan NE, Férard A, Ivanov S, Haltone P and Umstatter C 2020 Virtual fencing without visual cues: design, difficulties of implementation, and associated dairy cow behaviour. *Computers and Electronics in Agriculture 176*: 105613. https://doi.org/10.1016/j.compag.2020.105613

Marini D, Kearton T, Ouzman J, Llewellyn R, Belson S and Lee C 2020 Social influence on the effectiveness of virtual fencing in sheep. *PeerJ 8*. https://doi.org/10.7717/peerj.10066

Markus SB, Bailey DW and Jensen D 2014 Comparison of electric fence and a simulated fenceless control system on cattle movements. *Livestock Science 170*: 203-209. https://doi.org/10.1016/j.livsci.2014.10.011

Metz-Stefanowska J, Huijsmans PJM, Hogewerf PH, Ipema AH and Keen A 1992 Behaviour of cows before, during and after milking with an automatic milking system. In: Ipema AH, Lippus AC, Metz JHM and Rossing W (eds) *Prospects for Automatic Milking* pp 289-295. Pudoc Scientific Publishers: Wageningen, The Netherlands

Midwest Rural Energy Council (USA) 2005 *Installation and Operation of Electric Fences, Cow Trainers and Crowd Gates.* https://mrec.org/publications_2/

Miles AD 1951 Electric fence for distribution of cattle on a range grazed by sheep and cattle. *Rangeland Ecology & Management/Journal of Range Management Archives 4*: 228-232. https://doi.org/10.2307/3894331

Morgan N 2016 The role of portable electric fencing in biodiversity-friendly pasture management. *Renewable Agriculture and Food Systems 31*: 2-8. https://doi.org/10.1017/S1742170515000058

Morgan-Davies J and Waterhouse T 2015 Cattle responses to a type of virtual fence. *Rangeland Ecology & Management 68*: 100-107. https://doi.org/10.1016/j.rama.2014.12.004

NoFence Grazing Technology undated a *Virtual fencing for cattle.* https://www.nofence.no/en/product/cattle

NoFence Grazing Technology undated b *Virtual fence for goat and sheep.* https://www.nofence.no/en/product/goat-and-sheep

Oltenacu PA, Hultgren J and Algers B 1998 Associations between use of electric cow-trainers and clinical diseases, reproductive performance and culling in Swedish dairy cattle. *Preventive Veterinary Medicine 37*: 77-90. https://doi.org/10.1016/S0167-5877(98)00109-3

Paranhos da Costa MJR and Broom DM 2001 Consistency of side choice in the milking parlour by Holstein-Friesian cows and its relationship with their reactivity and milk yield. *Applied Animal Behaviour Science 70*: 177-186. https://doi.org/10.1016/S0168-1591(00)00158-1

Pearsall J 1998 *The New Oxford Dictionary of English.* Clarendon Press: Oxford, UK

Polikarpus A, Kaart T, Mootse H, De Rosa G and Arney D 2015 Influences of various factors on cows' entrance order into the milking parlour. *Applied Animal Behaviour Science 166*: 20-24. https://doi.org/10.1016/j.applanim.2015.02.016

Reinemann DJ, Stetson LE, Reilly JP and Laughlin NK 1999 Dairy cow sensitivity to short duration electrical currents. *Transactions of the American Society of Agricultural Engineers 42*: 215-222. https://doi.org/10.13031/2013.13198

Riber AB 2010 Development with age of nest box use and gregarious nesting in laying hens. *Applied Animal Behaviour Science 123*: 24-31. https://doi.org/10.1016/j.applanim.2009.12.016

Rigalma K, Duvaux-Ponter C, Barrier A, Charles C, Ponter AA, Deschamps F and Roussel S 2010 Medium-term effects of repeated exposure to stray voltage on activity, stress physiology, and milk production and composition in dairy cows. *Journal of Dairy Science 93*: 35-52. https://doi.org/10.3168/jds.2009-2903

Robinson MN, Brooks CG and Renshaw GD 1990 Electric shock devices and their effects on the human body. *Medicine, Science and the Law 30*: 285-300. https://doi.org/10.1177/106002809003000403

Rutland Electric Fencing (UK) undated *Fencing Tips*. https://www.kerbl.co.uk/products

Schewe RL and Stuart D 2015 Diversity in agricultural technology adoption: how are automatic milking systems used and to what end? *Agriculture and Human Values 32*: 199-213. https://doi.org/10.1007/s10460-014-9542-2

Scotton G 2019 Taming technologies: crowd control, animal control and the interspecies politics of mobility. *Parallax 25*: 358-378. https://doi.org/10.1080/13534645.2020.1731004

Stádník L, Louda F, Bezdíček J, Ježková A and Rákos M 2010 Changes in teat parameters caused by milking and their recovery to their initial size. *Archiv für Tierzucht 53*: 650-662. https://doi.org/10.5194/aab-53-650-2010

Stuart D, Schewe RL and Gunderson R 2013 Extending social theory to farm animals: addressing alienation in the dairy sector. *Sociologia Ruralis 53*: 201-222. https://doi.org/10.1111/soru.12005

Tannenbaum J 1999 Ethics and pain research in animals. *ILAR Journal 40/3*: 97-110. https://doi.org/10.1093/ilar.40.3.97

Tesfaye T, Sithole B, Ramjugernath D and Mokhothu T 2018 Valorisation of chicken feathers: characterisation of thermal, mechanical and electrical properties. *Sustainable Chemistry and Pharmacy 9*: 27-34. https://doi.org/10.1016/j.scp.2018.05.003

Umstatter C 2011 The evolution of virtual fences: a review. *Computers and Electronics in Agriculture 75*: 10-22. https://doi.org/10.1016/j.compag.2010.10.005

Verdon M, Horton B and Rawnsley R 2021a A case study on the use of virtual fencing to intensively graze Angus heifers using moving front and back-fences. *Frontiers in Animal Science 2*: 663963. https://doi.org/10.3389/fanim.2021.663963

Verdon M, Langworthy A and Rawnsley R 2021b Virtual fencing technology to intensively graze lactating dairy cattle. II: Effects on cow welfare and behavior. *Journal of Dairy Science 104*: 7084-7094. https://doi.org/10.3168/jds.2020-19797

Vidali G, Silversides FG, Boily R, Villeneuve P and Joncas R 1996 Effects of chopped sinusoidal voltages on the behavior and performance of laying hens. *Canadian Agricultural Engineering 38*: 99-106

Vroegindeweij BA, Kortlever JW, Wais E and van Henten EJ 2014 Development and test of an egg collecting device for floor eggs in loose housing systems for laying hens. *Proceedings International Conference of Agricultural Engineering AgEng, C0366. EurAgEng*. 6-10 July 2014, Brussels, Belgium

Warner RD, Ferguson DM, Cottrell JJ and Knee BW 2007 Acute stress induced by the preslaughter use of electric prodders causes tougher beef meat. *Australian Journal of Experimental Agriculture 47(7)*: 782-788. https://doi.org/10.1071/EA05155

Wenzel C, Schönreiter-Fischer S and Unshelm J 2003 Studies on step-kick behavior and stress of cows during milking in an automatic milking system. *Livestock Production Science 83*: 237-246. https://doi.org/10.1016/S0301-6226(03)00109-X

Whiting TL 2016 Pain in human and non-human animals caused by electricity. *The Canadian Veterinary Journal 57*: 883-886

Winter A and Hillerton JE 1995 Behaviour associated with feeding and milking of early lactation cows housed in an experimental automatic milking system. *Applied Animal Behaviour Science 46*: 1-15. https://doi.org/10.1016/0168-1591(95)00628-1

Worley JW and Wilson JL 2000 Effects of stray voltage on laying habits of broiler breeders. *Applied Engineering in Agriculture 16*: 723-729. https://doi.org/10.13031/2013.5369