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On-farm culling methods used for pigs

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Abstract

*The culling of injured and non-viable pigs (*Sus scrofa*) (neonate to breeding stock) is a routine and necessary procedure on most farms. Usually, pigs are culled using one of the following methods: blunt-force trauma (manual and mechanical), captive-bolt stunners, electrical stunning and electrocution or carbon dioxide. Manual blunt-force trauma is one of the most widely used methods due to its low or absent operational and investment costs. However, as a method, it has serious limitations, which include the risk of incomplete concussion, pain, and distress. Manual blunt-force trauma is also aesthetically unpleasant to operators and wider society. To address these issues there has been significant recent research into the development of alternatives to manual blunt-force trauma, these include: captive-bolt stunners, on-farm, gas-based controlled atmosphere systems, low atmospheric pressure systems and electrical stunning. Some of these are currently in commercial use while others are still in the developmental phase. This review brings together the relevant research in this field, evaluating the methods in terms of mechanism of action (mechanical and physiological), effectiveness and animal welfare.*

Keywords: *animal welfare, culling, killing, neonate, pig, suffering*

Introduction

Inevitably, injured, ill or weak animals must be culled during the production cycle to end further suffering. In animal production industries, leaving animals to die that are non-viable, injured, sick or suffering is not ethically justifiable. The stockperson is largely responsible for deciding the appropriate and legal method and moment to cull the animal. Ideally, the least stressful and unpleasant method that provides a rapid loss of consciousness, a quick death and is not aesthetically unacceptable to the general public should be used (Council Directive 1099/2009 2009; CFMV 2012).

Typical methods used for culling pigs (*Sus scrofa*) on-farm are: head trauma (Whiting *et al* 2011; CFMV 2012; American Veterinary Medical Association [AVMA] 2020), electrical stunning (CFMV 2012; AVMA 2020) and carbon dioxide (CFMV 2012; Sadler *et al* 2013, 2014; AVMA 2020). When performed correctly these methods are effective for culling pigs. However, there are the disadvantages of: i) costs to the farmers; ii) complexity of operation and training required; iii) potential for welfare compromise; and iv) psychological effects of the practice on stockpeople. Furthermore, the ideal culling method for pigs on-farm should not be so aesthetically unpleasant as to appear cruel to the general public, as this can impact on the perception and reputation of the industry. The choice of a humane culling method for pigs is a subject of debate in the pig industry. A recent survey in Brazil showed concussion (90%) to be the most used method for on-farm pig culling (Dalla Costa *et al* 2019). However, stockpeople who used concussion methods (such as striking a piglet's head against the wall/floor or with a hammer) felt uncomfortable and would prefer to use other methods (Rawnsley 1985; Rault *et al* 2017; Grist *et al* 2018a,b,c; Dalla Costa *et al* 2019). Therefore, the literature on culling methods for pigs was reviewed to identify the knowledge gaps and compare methods in relation to animal welfare.

Culling methods

Concussion

Concussion is the most widely used on-farm culling method for rendering pigs irreversibly unconscious (Matthis 2005; Dalla Costa *et al* 2019). Concussion can be achieved through mechanical methods, such as penetrating and non-penetrating captive-bolt stunners (Finnie *et al* 2000;

Oliveira *et al* 2018; Dalla Costa *et al* 2019), and by manual methods such as striking the head of the animal either with a heavy and rigid tool, or in the case of small/young animals, against a rigid and flat surface (Council Directive 1099/2009 2009; CFMV 2012; AVMA 2020). These methods depend on the transfer of kinetic energy to the brain (Farouk 2013; Oliveira *et al* 2017, 2018). The main difference between the penetrating and non-penetrating methods is that the first is designed to penetrate the cranium, reach the brain and to irreversibly damage its architecture. The second is designed to induce unconsciousness through the impact of a non-penetrating wider bolt against the skull, unconsciousness may be reversible or not depending on the severity of the blow.

With non-penetrating methods, such as non-penetrative captive-bolt stunners (CBS), concussion against a wall or blunt force applied with a hammer, the acceleration/deceleration forces provide great kinetic (momentum), rotation and shear forces to the head and the brain. In quadrupeds, the longitudinal axis of the brain is continuous with the spinal cord. This almost linear neuraxis, along with the falx, tentorium and cranial nerves, helps reduce the action of rotational forces of the impact and can render the animal less vulnerable to concussion (Finnie *et al* 2001). In addition, the brains of these animals are better protected than in humans by well-developed temporal muscles and large frontal sinuses. In contrast, the penetrating method provides high focal kinetic energy and force but produces relatively low momentum (Ommaya *et al* 2002). The purpose of this method is to induce a profound and irreversible form of concussion (Gregory *et al* 2007), since there is destruction of brain tissue in the permanent cavity produced by the bolt, which is surrounded by a haemorrhagic zone (Finnie 2016; Oliveira *et al* 2018). For both methods, loss of consciousness is caused by the combination of direct damage to the brain and by the amount of kinetic energy transmitted to the animal's head (Gibson *et al* 2015b; Oliveira *et al* 2017, 2018).

Currently, manual blunt-force trauma is accepted as an effective method of culling piglets up to 5 kg (Haley *et al* 2008; Widowski *et al* 2008; Council Directive 1099/2009 2009; AVMA 2020). This technique involves strongly striking the top of the piglet's cranium against a flat and rigid surface by holding the rear legs or even around the loin (ie around the abdomen immediately cranial to the hind limbs). Stockpeople can also strike the piglet's head against the top of a wall of a pig pen, using a downward motion. The advantage of this method is that the hand follows through with little risk of it hitting the wall or floor, and so the operator is more likely to be confident in using a larger swing and greater force.

Compared to other methods, manual blunt-force trauma requires little or no capital or operational costs and is perceived to have advantages in terms of ease of use. However, striking the pig's head is questionable due to its risks of ineffectiveness (Grist *et al* 2018c; Dalla Costa *et al* 2019), animal welfare concerns (Council Directive 1099/2009 2009; Grist *et al* 2018a,b,c) and it being an aesthetically unpleasant method (Grist *et al* 2018c; Dalla Costa *et al* 2019) that can be perceived as cruel and repulsive by the general public (Grist *et al* 2018c; Kells *et al* 2018; Dalla Costa *et al* 2019).

The skull is relatively thin and the extended fractures are caused by the impact of the trauma when struck against a rigid surface (Figure 1[b]). Despite this level of damage, the efficiency and consistency of manual blunt-force trauma is debatable (Woods *et al* 2010). Incomplete concussion can occur in cases of insufficient trauma to the head or if the body and shoulders take the impact. Incomplete concussion can occur especially if the stockperson is not comfortable in performing culling or is not experienced with the method, skilled and trained. Reasons for incomplete concussion include: insufficient force employed; incorrect impact site; low strike velocity; operator fatigue; large size and weight of the animal; and skull morphology (Gibson *et al* 2015b, 2019; Oliveira 2017; Walsh *et al* 2017; Grist *et al* 2018c; Oliveira *et al* 2018). When there is incomplete concussion, animals will take longer to die or might recover and could suffer from the initial impact. The correct performance depends on the force applied to the head, operator experience, adequate training, and the frequency of performance (Gibson *et al* 2015b; Oliveira *et al* 2017; Dalla Costa *et al* 2019). Dalla Costa *et al* (2020) reported 100% of piglets (0.35 to 1.17 kg) had no brainstem reflexes and isoelectric electroencephalograms (EEG) after being struck against the floor. Based on reflexes only, the use of blunt-force trauma (by striking a piglet's head with a 227 g hammer), showed a high failure rate (12%; 6/50) which was similar to that found in other species (22%) (Walsh *et al* 2017). Despite the potential for extensive brain and skull damage, these results suggest a variability of effectiveness during manual blunt-force trauma in practice. In addition, once a piglet starts to convulse after concussion, re-stunning becomes difficult, both physically and psychologically for the stockperson.

The convulsive activity is hypothesised to occur due to the loss of inhibitory control from the higher centres of the brain when the spinal cord is still active (Nilsson & Nordström 1977; Velarde & Raj 2016a). It is more dangerous and difficult to handle and stick (bleed) an animal during the convulsive phase. Options for controlling or reducing convulsive kicking include: (i) destroying the brain with a cane or rod (pithing); (ii) pneumatic pithing (compressed air injection after shooting); (iii) inducing spinal cord damage; (iv) inducing a cardiac arrest at or immediately after stunning; (v) electrical spinal discharge or electroimmobilisation; (vi) prompt sticking; and (vii) sticking before shackling (Gregory 2007).

Captive-bolt stunners (CBS)

A limited number of studies have evaluated the efficacy of CBS for pigs on-farm (Figure 2). The use of CBS can be an effective mechanical alternative to blunt-force trauma, with the advantages of improved animal welfare (when performed correctly), ease of use and improved aesthetic acceptability. To be used correctly CBS requires: (i) restraint of the animal; (ii) selection of the appropriate gun and cartridge combination for the stage of production; (iii) correct maintenance; (iv) appropriate bolt length; and (v)

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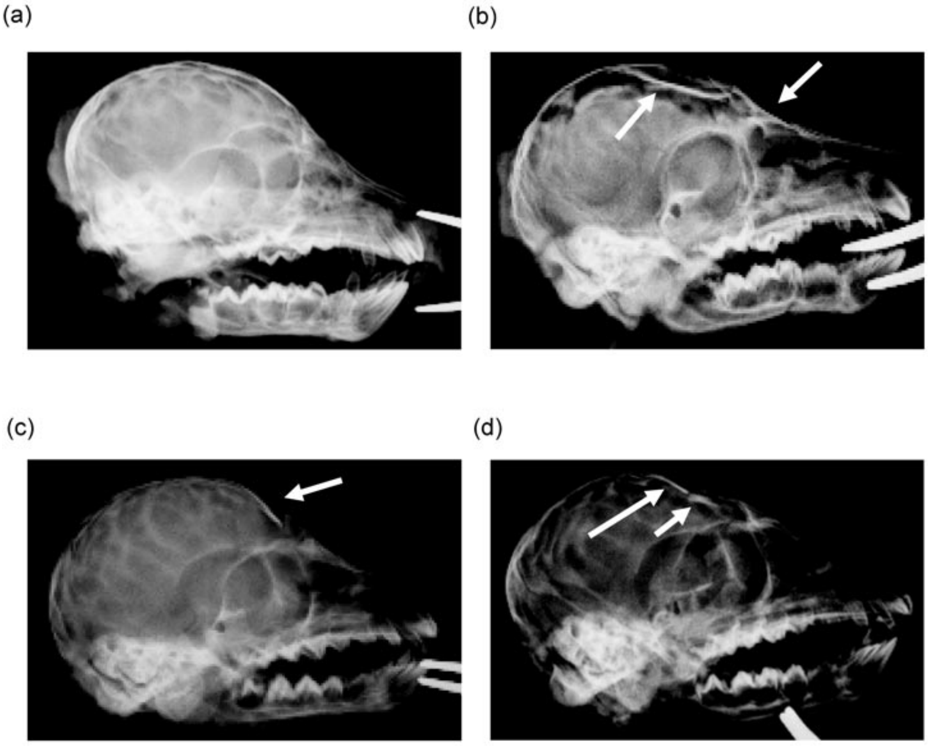
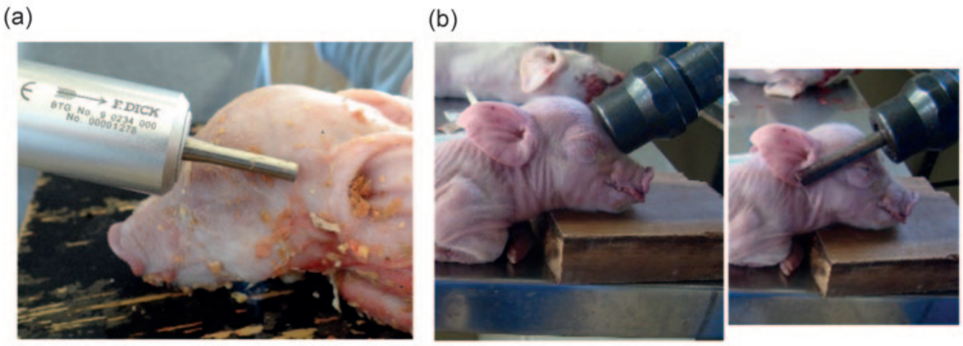
Figure 1



Radiographic images of piglets' heads (< 2 kg) dispatched using the following methods: (a) electrocution (no fractures), (b) struck with a hammer (extended fractures and fragments in frontal and parietal bone), (c) shot with a spring-powered captive-bolt stunner (CBS) (focal and small fracture and fragment in the frontal bone) and (d) shot with a cartridge CBS (extended fracture and fragments in the frontal bone).

Figure 2



Demonstration of shooting using (a) spring- and (b) cartridge-powered penetrating captive-bolt stunner (CBS) types (visualisation of placement prior to shot and penetration depth).

correct positioning and orientation of the gun relative to the skull to ensure maximal trauma and transfer of energy to vital brain structures. Usually, sick and/or injured animals are physically weak and do not move intensively. However, it can be difficult to restrain some animals due to their size/weight and the location of the animal at the required time of culling. With these animals, restraining the head using a rope in the mouth and/or placing the body in a hammock or cradle can help to minimise movement and improve shot effectiveness at the right angle and position.

Work by Widowski *et al* (2008) examining the use of the non-penetrating CBS (Zephyr Stunner, pneumatic version, Bock Industries Inc, Philipsburg, PA, USA) reported that 85% of piglets were rendered immediately unconscious. However, the authors reported that the Zephyr stunner should not be recommended due to some animals (15%) being incompletely concussed and presenting signs of returning to consciousness (Widowski *et al* 2008). In a follow-up study by the same group, the device and technique used were improved, and the modified Zephyr-

EXL was recommended as a humane method for culling piglets (from birth until 49 days of age; 9 kg). It was reported that the Zephyr-EXL produced loss of clinical signs of consciousness, irreversible brain injuries and death within, on average, 3.75 min in 100% of piglets (Casey-Trott *et al* 2013, 2014). Similar effectiveness using the Zephyr-EXL was later found by other groups for piglets of 10.9 kg (Grist *et al* 2017), confirming that the method can be a satisfactory alternative.

However, depending on the size and age of the pigs, the non-penetrating method may not be an effective method of stunning. In growing pigs (15–18 kg), non-penetrating CBS (Schermer - inline type, Karl Schermer & Co, Karlsruhe, Germany) caused a fracture in the outer table of the skull and mild haemorrhages in the subarachnoid and base of the brain in only 33% (2/6) of the animals tested, without causing fractures in the inner table (Finnie *et al* 2003). In other species penetrating CBS has been reported as being more effective (fewer animals showing clinical signs of consciousness) than non-penetrating stunners (Gibson *et al* 2012, 2019; Sharp *et al* 2015; Oliveira *et al* 2018). There were more extensive fractures in the skulls of sheep shot with penetrating than non-penetrating captive bolt (100 vs 50%, respectively) (Finnie *et al* 2000). Macroscopic examination found that penetrating CBS produced a large, deep and defined haemorrhagic lesion through the cortical region extending into basal ganglia and thalamus, with focal haemorrhage in the medulla and pons. Non-penetrating CBS with a kinetic energy of 24 J (Table 1; see supplementary material to papers published in *Animal Welfare*: https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material) caused skull fracture in 100% of piglets with up to 3.9-mm thickness (Casey-Trott *et al* 2014) and widespread brain haemorrhages (varying from moderate to severe scores). Meanwhile, Finnie *et al* (2000) reported focal haemorrhage in only one side of the central white matter, rostral brainstem and thalamus, with no contralateral contusion in lambs. High scores of subcutaneous, subdural and brain haemorrhage in hindbrain, mid-brain and cortex areas were also reported for rabbits (*Oryctolagus cuniculus*) euthanased with non-penetrating CBS (Walsh *et al* 2017). The frontal cortex is responsible for sensory processing and signalling to the brainstem (Shaw 2002; Gaetz 2004). This brain region is directly affected by a correctly placed CBS shot. In addition, the presence of haemorrhage and blood clots increases intracranial pressure which is a lethal condition even in the case of small haemorrhages (Young & Destian 2002). Based on the severe brain damage (focal and diffuse lesions) and loss of clinical signs of sensibility, which were caused by direct physical trauma, the use of penetrating methods of culling was considered effective for several species such as alpaca (*Vicugna pacos*) (Gibson *et al* 2015c), sheep (*Ovis aries*) (Finnie *et al* 2000) and cattle (*Bos taurus*) (Oliveira *et al* 2018). Although penetrating CBS may be effective for culling small pigs, mature pigs (finishing pigs, sows, boars) need greater kinetic energy values and bolt lengths to compensate for energy dissipated traversing the large frontal sinuses or fracturing of the thick caudal skull bones and to cause enough brain damage to induce unconsciousness (Blackmore *et al* 1995).

Although CBS is effective for some species (Finnie *et al* 1999, 2000, 2001; Oliveira *et al* 2018; Gibson *et al* 2019), differences in head anatomy between species and individuals within the species may influence the transfer of kinetic energy and angular acceleration forces from the moving bolt to the brain. Figure 1 shows the skull fractures in piglets caused by different culling methods from an unpublished pilot test (Dalla Costa, in prep). Compared to a spring-powered penetrating CBS, a more powerful cartridge CBS (Figure 1[d]), with greater kinetic energy, with a longer bolt, resulted in more extended fractures and fragments in the frontal bone. Although fractures caused by hammer (Figure 1[b]) were similar to the cartridge CBS, the mechanism and the resulting brain damage are different.

Unlike young pigs that have a rounded head shape, adult pigs present a skull with a triangular shape (lateral aspect including the mandible), large frontal sinuses, curved cranial cavity floor, elongated and relatively narrow brain, and short and wide cerebellum (Finnie *et al* 2003). Relatively larger frontal sinuses than found in other species may reduce the transmission efficiency of kinetic energy at the time of impact of the bolt with the frontal region of the head. In addition, well developed neck muscles can reduce the action of angular acceleration after the impact, resulting in less severe brain lesions (Blumbergs 1997; Graham & Gennarelli 1997; Finnie *et al* 2003). Longer bolts than those commercially available could potentially improve the effectiveness of CBS culling of adult pigs. The larger frontal sinuses than found in other production animal species reduce the potential for extensive brain trauma, particularly to brainstem structures. Studies with cattle with longer bolts (length of 17.8 vs 16.5 vs 15.2 cm) reported greater damage to brain tissue (Kline *et al* 2019; Wagner *et al* 2019), deeper penetration depth, larger penetration hole diameter and more damage to deeper brain regions such as: hypothalamus, corpus callosum, fornix, and thalamus (Wagner *et al* 2019).

Incomplete concussion from defective or incorrectly applied CBSs can result in pain and stress. When an animal presents any signs of return of consciousness (including gasping behaviour), an extra shot should be fired in the correct position with the intention of causing brainstem damage (Gibson *et al* 2018). Structures within the brainstem are responsible for rhythmic breathing and cardiac control (Shaw 2002). Based on EEG assessment, incompletely concussed piglets (31 days old) may return to consciousness 25 s after stunning and an isoelectric EEG occurs 115 s after exsanguination (Blackmore & Newhook 1981).

Spring-powered CBSs have been developed for use in rabbits and it has been proposed that these could be effective for injured and non-viable piglets. However, work in pouch-young kangaroos (*Macropodidae*) has shown that spring-powered CBSs are ineffective (Dick KTBG, Friedr Dick GmbH and Co, Deizisau, Germany; and Finito 244, Klaus-

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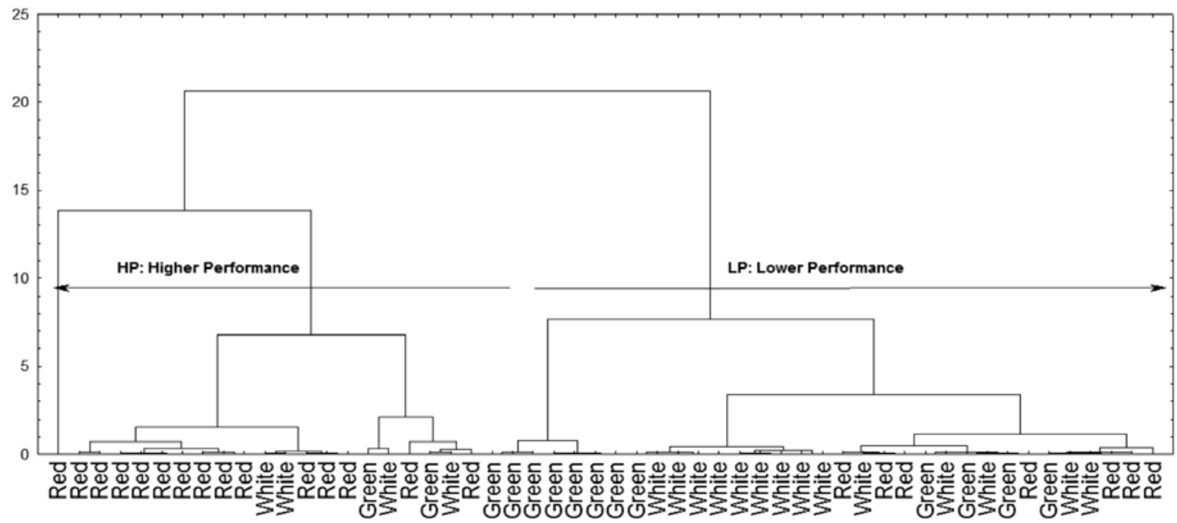
Figure 3



Dendrogram formed by cartridges (red cartridges: 5 grain; green: 4 grain; and white: 3 grain) performance variables (bolt velocity and kinetic energy) from the 54 shots using .22 GIL Umana gun type. The x-axis is the performance index classification and y-axis the cluster distance. CBG was shot into a velocity meter (2009 CBG Tester®, Royal Veterinary College, UK) to obtain a profile of bolt velocity. Peak velocity was recorded and used to calculate the kinetic energy of the bolt (kinetic energy = [0.5 × mass] × v2). Performance of captive-bolt stunner (CBS) means bolt velocity and kinetic energy (Dalla Costa *et al* 2016).

Gritsteinwerk GmbH and Co, Bünde, Germany; Table 1; https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material). Younger animals may be more resistant to concussive trauma, associated with their softer, less ossified craniums (Svendsen *et al* 2008; Sharp *et al* 2015). Thus, based on the effectiveness and anatomical differences, specific studies for each species according to age and size are needed to define the appropriate humane culling methods.

It is recommended when possible with both blunt-force trauma and captive bolt, that a secondary procedure such as exsanguination (bleeding) or pithing (penetrating CBS only) is performed to reduce the potential for recovery of consciousness and hence protect animal welfare. This is an important recommendation because there is no direct cardiac arrest or severance of the spinal cord and carotid arteries with concussion methods. Generally, an interval not longer than 15 s between stunning and application of the secondary method is accepted by most animal welfare recommendations. However, independent of the method used, the interval between the culling and bleeding should be the shortest possible to ensure a humane death for methods which do not induce cardiac arrest (Anil & McKinstry 1992). Most of these recommendations are based on electrical stunning studies where there is no macroscopic brain destruction. Under special conditions, such as disease control, both penetrating and non-penetrating captive-bolt stunners could be used as a single step culling method to minimise environmental contamination and protect human safety. However, there are no studies evaluating the necessity of bleeding for concussive methods, but it appears to be mostly dependent on the level of brain damage.

CBS performance with different cartridge powers

A study comparing the performance of different Brazilian-manufactured cartridges that were used to cull pigs with the .22 GIL Umana gun (Gil Equipamentos Indutriais, Ribeirão Preto, SP, Brazil) reported no differences in means of peak velocity and kinetic energy (data presented in Table 1; https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material) (Dalla Costa *et al* 2016). Not surprisingly, cluster analysis showed the highest performance (HP) group (x-axis) was mostly formed by higher powered red cartridges (5 grain) (15 from a total of 21 shots), while the lowest performance (LP) group was mostly formed by white (3 grain) (14/33) and green (4 grain) (12/33) cartridges (Figure 3) (Dalla Costa *et al* 2016). However, a high variability between cartridges from the same category was found. Some of the red cartridges presented the lowest performance shots, and some white cartridges were positioned close to highest performance shots.

The performance of cartridge-powered CBS can be affected by factors such as: powerload; packing volume; storage of the cartridges and gun in damp conditions, which influences the burning of gunpowder; and regular maintenance of the stunner, mainly the removal of excessive residue build-up in CBS barrel and around the rubber buffers (Grandin 1980, 1994, 2002; Gregory & Shaw 2000; Gibson *et al* 2015b; Anon 2016; Grist *et al* 2019). The performance variation within the same cartridge colour can indicate variations in quality assurance during manufacturing. The literature highlights similar issues with the variability in cartridge performance (Gibson *et al* 2015b; Grist *et al* 2019), which have been reported as being associated with cartridge fill. For the

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Table 4 Performance of free bullet pistols that could be appropriate for pig culling according to their type and ammunition.

Factor	9 mm Pistol; semi-automatic Colt pistol	.45 Pistol; semi-automatic Colt pistol	.32 Accles and Shelvoke Cash Humane Killer
Bullet, ammunition, grain	Metal, jacket round, 124 grain	Metal, jacket round, 230 grain	5.51 g
Distance of shooting (m)	3	3	–
Shot position (head)	Frontal	Frontal	–
Velocity (ms^{-1})*	–	–	–
Kinetic energy (J)*	427.85	747.16	–
Species	Cattle	Cattle	Horses
Effectiveness**	33.33% (2/6)	100% (6/6)	100% (15/15)
Reference	Thomson *et al* (2013)	Thomson *et al* (2013)	Millar & Mills (2000)

* Peak or range of velocity or kinetic energy;
** Effectiveness was evaluated in carcase body (head only).

data presented above for the .22 GIL Umana, the kinetic energy found for these guns was greater than reported in the literature to stun mature bulls using different gun types (127–200 J) (Blackmore 1985; Gibson *et al* 2012). Thus, in theory, these unpublished findings from the testing of .22 GIL Umana, Cash Special (5 grain Red; Accles & Shelvoke Ltd, Minworth Sutton Coldfield, UK) and CTrade TEC 10 (4 grain green; CTrade Ltd, Cachoeirinha, RS, Brazil) suggests that the tested CBS/cartridge combinations could potentially be effective to stun/kill pigs through the different stages of production. The captive-bolt stunners developed for buffalo stunning, such as Magnum XL with 6-grain cartridges (Accles and Shelvoke Ltd) and the Schermer KL (Karl Schermer GmbH & Co), could be an alternative for adult pigs (de la Cruz *et al* 2018). However, further studies are required examining the minimum kinetic energy required to stun mature pigs using CBS, responsiveness after stunning, gross brain pathology, and variations in skull anatomy before any recommendations are made.

Free-bullet firearms

Free-bullet firearms are also used to cull adult pigs on-farm. Tables 2 and 3 (see supplementary material to papers published in *Animal Welfare*: https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material) and 4 (above) show the performance of different gun types and ammunition to cull animals on-farm. Due to the greater projectile velocity (580–770 ms^{-1}), even a small mass projectile fired at the head delivers significantly more energy than the CBSs (Anil 2012; Gibson *et al* 2012, 2015a,b; Schiffer *et al* 2014). With free bullet, loss of consciousness is caused by the amount of kinetic energy delivered and brain laceration. Based on brain lesions in structures related to loss of consciousness, the use of various firearms/ammunition (.45 pistol, .223 carbine and 12 gauge shotgun) can be effective for culling (Thomson *et al* 2013). Solid and buckshot projectiles of 16-mm diameter fired from a 12-gauge shotgun penetrated the skull of boars and sows (Blackmore *et al* 1995), while a 9-mm projectile with 178 J did not penetrate the skull of finishing pigs (75 kg) (Blackmore 1985; Blackmore *et al* 1995) and caused insufficient damage to ensure a rapid death (Blackmore *et al* 1995; Thomson *et al* 2013). Anecdotally, it has been observed that for some adult boars even solid shot from a 12-gauge shotgun when fired within 50 cm of the head has insufficient energy to penetrate through to the cranial vault and enter the brain to cause unconsciousness and death (T Gibson, personal communication 2018). However, Burnet (1991) reported some bone particles in the brain of pigs shot in the head that can cause enough damage to the brain and unconsciousness. When shots enter at the recommended shooting position where the bone is thinner, variation in projectile angle changes the bullet trajectories and this can significantly influence the severity of brain damage (Millar & Mills 2000).

Effectiveness during the use of captive-bolt or free-bullet guns is determined by the following factors:

- Selection of the appropriate gun type for the species and/or stage of production;
- Cartridge strength (determined by grain size or mg load) and bolt length;
- Adequate storage of cartridges: no moisture;
- Bolt velocity and amount of kinetic energy transferred to the animal's head;
- Animal restraint;
- Operator training/experience and fatigue;
- Hitting the right target area (variations between animal size and shot angle); and
- Severity of brain damage.

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Electrical

Electrical methods of stunning and culling involve passing electrical current through the pig's head to cause instantaneous insensibility and unconsciousness by inducing a tonic/clonic epileptic fit. This should be done prior to applying current across the heart to induce cardiac arrest, or a secondary procedure (bleeding, head trauma or cardiac compression) or by using high current levels that produce irrecoverable loss of consciousness. The aim with all electrical stunning and culling methods is to rapidly cause unconsciousness and insensibility prior to the perception of pain associated with the method. In mammals, it has been reported that electrical stunning should induce unconsciousness within 100 ms of application to prevent the transmission of nociceptive impulses via the central nervous system from being perceived as pain (100–150 ms) (Wotton 1996).

Several devices (such as mobile units smaller than those used in abattoirs and home-made devices) are used to cull pigs by electrical stunning. Ideally, mobile electrical stunners should have a transformer, safety box and two electrodes which are applied to the animal's head (Denicourt *et al* 2010; Mores & Mores 2014). Electrical stunning can be performed in different ways. It can be done by applying current across the head only (head-only stunning) or followed by a second current applied to the chest, laterally in the chest and at the heart position (head-to-chest/brisket stunning) or on the back (head-to-back stunning) to induce cardiac ventricular fibrillation. If a head-only stun is used it is essential that a secondary procedure such as bleeding or head trauma is performed to prevent recovery. However, some home-made devices, which are often illegal (both in terms of operator health and safety and animal welfare) vary in the position of electrode application and electrode shape (for instance, some use alligator clips) which are usually applied at the ear and groin or tail (FA Dalla Costa, personal observation 2018). There are significant animal welfare and operator health and safety issues with these home-made devices. The application of alligator clip electrodes, which are often large clips from car jump leads can cause pain. Insufficient electrical current can also cause electro-immobilisation without loss of consciousness, where the animal can no longer voluntarily move or utilise the muscles of respiration, death can be due to hypoxaemia (AVMA 2008). However, this method is potentially attractive to operators as it is low cost and reduces post-stun clonic convulsions, due to the inhibition of spinal cord function.

For use on farms, home-made devices connected to the domestic power source (110 or 220 V, 50–60 Hz) usually do not guarantee the minimum current of 1.3 A recommended (EFSA 2004). When used with electrodes in good condition and correctly positioned on the pigs' head, a minimum voltage of 240–250 V is necessary to reach the required current flow (EFSA 2004; Denicourt *et al* 2010). For commercial electrical stunning, the stun must be applied properly to deliver a minimum current of 1.3 A continuously during at least 1 s to ensure that pigs are instantly rendered unconscious (Hoenderken 1978; EFSA 2004). Although it is thought that pigs lose consciousness faster than 1 s, this minimum stun duration is recommended due to the ease of measurement and to ensure an effective stun. One study reported that 400 mA was sufficient to cause effective stunning for younger animals (Llonch *et al* 2015) which might be explained by the lower impedance of the animal (Gregory & Wotton 1984). However, the use of higher currents is recommended to ensure effective stunning.

Controlled atmosphere stunning with gas

The inhalation of carbon dioxide (CO_2) reduces the pH of blood and cerebrospinal fluid, which causes respiratory, metabolic and brain cell intracellular acidosis, and eventually induces a state of unconsciousness in the animal (Lambooij *et al* 1999; Martoft *et al* 2003; Raj 2008b). Due to the decrease in intracellular pH (from 7.28 to 6.73) within 58 s, pigs can be anaesthetised by inhaling a high concentration of CO_2 (90%) (Martoft *et al* 2003). Supporting these findings, a high concentration of CO_2 was reported to reduce basal activity of brain and evoked potentials responses (Forslid 1987; Ring *et al* 1988; Raj *et al* 1997).

Currently, controlled atmosphere stunning can use immersion of pigs into a high concentration of the stunning gas or introduction of the stunning gas by gradual filling. In the immersion into a high concentration of gas stunning, pigs are placed into a closed box pre-filled with a high concentration of the gas (≥ 85–90%). To improve the effectiveness of stunning the minimum immersion time should be longer than 130 s, and should be at least 5 min for effective culling without need for bleeding (National Pork Board 2009). In high CO_2 concentrations (80–95%), Verhoeven *et al* (2016) reported pigs lose consciousness within 33–47 s, develop iso-electric EEG between 64–75 s, and lose posture 10 s prior to EEG-related loss of consciousness (transitional and isoelectric states). The authors reported earlier exhibition of behaviour related to discomfort (such as sniffing, retreat attempts, lateral head movements, jumping, and gasping) in high CO_2 concentrations. However, the use of gradual filling of gas (20% of the chamber volume per min) reduced the behaviours associated with discomfort. With gradual filling of CO_2, unconsciousness occurs prior to exposure to CO_2 levels associated with nociceptive stimulation of ocular or nasal mucosa (AVMA 2020). Further, most of the pigs evaluated did not demonstrate any aversion to the presence of 30% carbon dioxide in air (Raj & Gregory 1995). Despite the findings with gradual fill/displacement, the majority of commercial systems for stunning and slaughter of pigs for human consumption use immersion into high concentration CO_2.

Animals show aversive responses to CO_2 exposure (Anton *et al* 1992; Leach *et al* 2002, 2004). Even in a lower concentration (30–54%), human beings exposed to CO_2 experienced prickling sensations. Humans reported the thresholds for pain of: 31–34% CO_2 for corneal (Chen *et al* 1995; Feng & Simpson 2003); 54% CO_2 for conjunctiva (Feng & Simpson 2003); 40–50% CO_2 for nasal mucosa (Anton *et al* 1992; Danneman *et al* 1997; Thürauf *et al* 2002) and 48% for discomfort (Chen *et al* 1995). In addition to the noxious component of CO_2, there are concerns associated with the sensation of induced breathlessness (dyspnoea) and the experience of anxiety and distress prior to the onset of unconsciousness in a concentration of as low as 8% (Dripps & Comroe 1947; Liotti *et al* 2001; Beausoleil & Mellor 2015). The uncomfortable sensation of urgency to breathe is observed at the beginning of exposure to CO_2. This respiratory discomfort is called breathlessness or air hunger, and increases in response to CO_2 inhaled (Banzett *et al* 1996; Liotti *et al* 2001; Verhoeven *et al* 2016). Dyspnoea and air hunger are behaviours indicative of inadequate oxygenation. Prickle stimuli occurs due to acidosis of mucous membranes during CO_2 exposure which could be associated with distressing sensations. The metabolic acidosis induced by the CO_2 reduces cerebrospinal fluid pH (Banzett *et al* 2007; Velarde & Raj 2016b) and thus the animals lose consciousness due to both reduced cerebrospinal fluid pH (less than 7.1), the accumulation of extracellular potassium and energy deprivation (Velarde & Raj 2016b).

Several studies have investigated different gas mixtures to find a more effective rapid and humane death. Other gases, such as argon (Fiedler *et al* 2016) and nitrous oxide, (Rault *et al* 2013, 2015) are alternatives that have been suggested as less aversive for pigs. However, the literature is contradictory on conclusions for gas mixture use as well as type of exposure (gradual or immersion) (Raj 1999; Sadler *et al* 2014). From the animal welfare perspective, argon appears to be less aversive and more effective in suppressing evoked brain activity than CO_2. Pigs showed lower aversion to 90% argon than a gas mixture containing nitrogen and CO_2 (Dalmau *et al* 2010; Llonch *et al* 2012). Loss of posture can be considered the first sign of the progression towards loss of consciousness. Similar times to loss of posture (15–18 s) were found for 90% argon, 80–90% CO_2 and a mixture of 60% argon + 30% CO_2 (Raj 1999). Time to loss of evoked potential responses was shorter in 90% argon than gas mixtures (60% argon + 30% CO_2) or 90% CO_2 (Raj *et al* 1997). Although pigs lose sensibility faster in 90% argon, the authors reported a longer time to obtain an iso-electric EEG. Exposure to a mixture of 85% nitrogen and 15% carbon dioxide for 180 s was recommended to stun pigs (loss of consciousness occurring at approximately 48 s) to reduce stress behaviour (Anon 2010). Based on the literature, the following four gas mixtures could be considered for on-farm culling of pigs (Raj *et al* 1997; Raj 1999): (i) 5 min of exposure to 60% argon + 30 CO_2 followed by bleeding (within 45 s); (ii) 7 min of exposure to 60% argon + 30 CO_2; (iii) 7 min of exposure to 90% argon followed by bleeding; and (iv) exposure to 90% argon for longer than 7 min. However, based on behaviour observations (such as loss of posture, air hunger, ataxia and righting response) even in gradual filling or immersion, a gas mixture of 50% argon + 50% CO_2 did not show advantages for animal welfare or efficacy of culling for neonate and weaned piglets (Sadler *et al* 2014). The advantages of nitrous oxide (N_2O) are that it has analgesic, sedative, anxiolytic properties (Rault *et al* 2013). Due to its ease of handling (non-flammable, non-explosive, suppliers' availability, and low price), development of on-farm equipment to cull pigs using N_2O could improve animal welfare during culling procedures. However, a two-step process which uses an initial exposure to N_2O followed by CO_2 did not reduce the amount of distressful behaviours compared to CO_2 in piglets of up to seven days old (Smith *et al* 2018). Thus, the use of N_2O in a two-step system did not present welfare benefits for piglets when compared to CO_2. Also, it may be necessary to use an N_2O-scavenging system to avoid health hazards for the operators such as megaloblastic anaemia and peripheral neuropathy (Sweetman 2012).

Use of gas-filled foam as a culling method has been discussed within the scientific community (Berg & Raj 2015). The water-based foam uses medium or high expansion foam to create a blanket of water-based foam that envelops the animals. However, water-based foam can cause mechanical obstruction of the upper and lower respiratory tract by the bubbles and liquid due to its high density (McKeegan *et al* 2013a). Theoretically, obstruction might occur with a glottis spasm if/when foam causes upper respiratory tract irritation. The sensation associated with obstruction of the upper respiratory tract can include suffocation. To avoid this problem, a dry foam method was developed. In this foam, when the bubbles filled with either an inert gas or CO_2 are broken down by contact or movement of the animal, a localised atmosphere of gas is created that can cause an acute hypoxia and rapid death without resulting in mechanical obstruction (Raj 2008a). Foams with CO_2 and N_2 have been evaluated (McKeegan *et al* 2013a; Gurung *et al* 2018b). Although CO_2 generated a faster death in birds, N_2 presented more advantages such as better foam quality (high expansion) and lower aversiveness (McKeegan *et al* 2013a; Gurung *et al* 2018b). In addition, reduced operator contact with animals and reduced gas utilisation can make the technique more feasible for animal culling, especially in cases of sanitary problems where large groups have to be culled (Dawson *et al* 2006; McKeegan *et al* 2013a; Gurung *et al* 2018a,b). However, due to the prolonged time to unconsciousness for piglets (10–12 min) and slaughter pigs (convulsions ending 77 s after immersion in the foam) (Marahrens *et al* 2017), and signs of some animals regaining consciousness, N_2 foam needs significant refinements. Furthermore, studies evaluating different rates of foam expansion on animal welfare perspective should be conducted before its general use for stunning/culling pigs.

From a practical perspective, the use of containers and gas/foam devices may be a disadvantage and also more expensive than other methods commercially available, especially in cases when only one animal is required to be culled. The need for handling and inserting pigs into the containers may increase the risk of stress, pain or suffering for fatigued and injured pigs. Evaluation of the procedure during culling without removal of the pigs from the containers is difficult due to the limited access and the risk of disturbing the localised gas environment around the animal. In the case of unsuccessful culling, pigs should be immediately stunned using a back-up method such as a penetrating captive-bolt stunner.

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Table 5 Reflexes and behaviour response of piglets exposed to different pressures and ascension rates.

Pressure (kPa)	Altitude (m)	Ascension rate (m s^{-1})	Reflexes and behaviour responses	Animal description	N	Reference
27.22	9,200	6.7 m s^{-1}	Heavy breathing and loss of co-ordination	Nursery piglets (5.6 [± 1.3]) kg	6	Engle & Edwards (2010)
19.32	11,600	6.7 m s^{-1}	All pigs were lying down and breathing heavily	Nursery piglets (5.6 [± 1.3]) kg	6	Engle & Edwards (2010)
15.16	13,300	6.7 m s^{-1}	All movements ceased	Nursery piglets (5.6 [± 1.3]) kg	6	Engle & Edwards (2010)
15.16	13,300	6.7 m s^{-1}	Three piglets had minor to moderate lung congestion	Nursery piglets (5.6 [± 1.3]) kg	6	Engle & Edwards (2010)
19.36	11,600	36.9 m s^{-1}	The optimum ascension protocol to culling piglets based on the least amount of negative behaviour response. Similar behaviour response to 6.7 m s^{-1} ascension rate were reported	Nursery piglets	5	Engle & Edwards (2010)
6.6	18,000	36.9 m s^{-1}	Vocalisations and gasping within the first 5 min of exposure	Pigs	29	Buzzard (2012)

Low Atmospheric Pressure Stunning (LAPS)

LAPS is a recently developed system that stuns/culls animals through hypoxia caused by atmospheric pressure reduction. Air is gradually withdrawn through a vacuum pump, causing a reduction in atmospheric pressure and inspired oxygen partial pressure, with the animal becoming unconsciousness due to hypoxaemia. The use of LAPS for culling of pigs holds potential from an animal welfare perspective because animals could be stunned without being exposed to high concentrations of aversive/inert gases. In humans, consciousness and normal EEG pattern are lost when the level of brain tissue pO_2 are lower than 20 mm Hg (Pearigen *et al* 1996). Poultry studies using LAPS showed that an approximate 85% reduction in blood oxygen tension (Purswell *et al* 2007), is associated with 90% reduction of brain activity as represented by electroencephalogram power (EEG) (Raj 1998; Sandercock *et al* 2014) and loss of consciousness (Sandercock *et al* 2014).

Gradual pressure reduction allows the release of internal body gases without causing pain and discomfort (Smith 1965). During the initial phase of decompression (low fraction of inspired oxygen) humans reported a euphoric feeling (Van Liere 1943). Based on behavioural analysis of poultry, time to loss of posture and convulsions in LAPS was approximately 60–65 s (Vizzier-Thaxton *et al* 2010; Martin *et al* 2017). Suppression of EEG power occurred at 30 s (McKeegan *et al* 2013b). Martin *et al* (2017) reported EEG and ECG patterns indicating unconsciousness and bradycardia, respectively, at on average 50–60 s and ranging from 42–52 s after the beginning of the process, respectively. Although it could be due to retrograde amnesia, loss of consciousness was not reported as an uncomfortable or painful experience by humans induced with hypoxia in hyperbaric chamber (Smith 1965). Thus, when applied slowly, controlled and properly performed, the initial literature suggested that LAPS can be a humane method of stunning for poultry. Currently, the use of LAPS for broiler chickens is approved by EFSA (EFSA 2018).

Although studies using hypoxia have been widely performed and their effects are well understood, the literature on the use of LAPS with pigs is extremely limited. There are reported concerns on how to manage the pressure reduction to prevent painful expansion of trapped gases in body cavities and to promote the release of gases from the gastrointestinal tract and airways without compromising animal welfare (More *et al* 2017; Bouwsema & Lines 2019). Further work is needed to address these concerns about LAPS for pigs and to prove its benefits compared to controlled atmosphere systems with CO_2.

Some researchers have evaluated the LAPS system to cull piglets using EEG, ECG, behaviour observations and gross pathology (Table 5 and 6 [see supplementary material to papers published in *Animal Welfare*: https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material]). Using a gradual decompression rate (equivalent to an ascent rate of approximately 6.7 m s^{-1}), Engle and Edwards (2010) reported that pigs showed heavy breathing and loss of co-ordination at 27.22 kPa (9,200 m of altitude), all pigs were lying down and breathing heavily at 19.32 kPa (11,600 m of altitude), and all movements ceased at 15.16 kPa (13,300 m of altitude; approximately 37 min). Buzzard (2012) reported vocalisations and gasping within the first 5 min of exposure at 6.6 kPa (18,000 m of altitude). A study using inert gas reported that pigs usually lost consciousness at 2% oxygen within 15 s (Raj 1999) which would occur at 16 kPa. At this pressure, time to death is approximately 7 min (Raj 1999). However, age can affect the time to loss of consciousness and death. Edwards and Engle (2011) found a time to death between 15–29 min.

Based on behavioural observations, gross pathology and EEG, Edwards and Engle (2011) reported that an ascent rate of approximately 36.9 m s^{-1} to reach 19.32 kPa (11,600 m of altitude) was the most appropriate method for culling pigs due to the least amount of negative behavioural responses observed. However, due to the small sample size used and difficulties of EEG and behaviour data collection, more studies on moribund, healthy nursery and large pigs of different weights are needed to give a more reliable view of the animal responses to low atmospheric pressure in a commercial pigs' operation.

Prevention of worker accidents during on-farm culling

Reported accidents during on-farm culling are relatively uncommon (Dalla Costa *et al* 2019). From a total of 606 interviews of Brazilian stockpeople, Dalla Costa *et al* (2019) reported only four accidents, during the culling of finishing pigs (n = 2) and sows (n =2). These accidents could have occurred when using methods such as concussion with a solid object, electrocution using a home-made device or cardiac stab, which were the more commonly reported methods.

Concussion was usually performed with a hammer (Dalla Costa *et al* 2019). Accidents with this method could include the accidental striking of the operator(s) with the hammer when missing the animal's head. The home-made electrocution device was plugged to a power outlet (110/220 V; 60 Hz), without an electrical current control, and featuring two metallic clips, one applied on one ear and the other on the tail for at least 5 s (Dalla Costa *et al* 2019). The absence of a control box and non-isolated electrodes could electrocute the operator(s) in different intensities, from a weak electrical discharge to an electrocution with cardiac arrest and death. The potential danger of operator electrocution is further enhanced by the presence of wet floors as is commonly found in pig pens. There were only personal reports of accidents with the above discussed methods, highlighting a lack of systematic data.

Despite the concerns about accidents using CBS for animal culling (Matthis 2005), injuries caused by bolt stunners are rarely reported. The majority of reported cases relate to homicide (Betz *et al* 1993; Caird *et al* 2000; Simic *et al* 2007) and suicide (Caird *et al* 2000; Grellner *et al* 2000; Gnjidić *et al* 2002; Viola *et al* 2004; Viel *et al* 2009), with reported mortality rates of more than 60% (Gnjidić *et al* 2002; Kattimani *et al* 2016). Due to their physical features, captive-bolt stunners are not commonly used in homicides. Severe injuries can be caused only when guns are fired at a distance closer than 10 cm (Janssen & Stieger 1964; Betz *et al* 1993). Many on-farm, work-related accidents can be prevented with proper orientation and training programmes (Tordrup & Kjeldsen 1994; Whiting *et al* 2011; Casey-Trott *et al* 2014; Kattimani *et al* 2016). For instance, the reported case involving a man who accidentally shot his thigh while holding a calf between his thighs during on-farm culling (Kattimani *et al* 2016) could have been avoided by using a proper restraining technique.

The risk of injury to operator(s) using free-bullet can be reduced with the use of rounds that have insufficient velocity (hollow point or non-jacketed, soft-nosed rounds) to exit the head and neck (Blackmore 1985; Finnie 1993; Cooney *et al* 2012; Schiffer *et al* 2014). This reduces the potential for ricochets off bone or solid objects in the environment. To further reduce risk, the shooting area should have a safe background behind the pig to absorb any bullets that exit the animal to further prevent ricochets. All operators must be positioned behind the muzzle of the firearm, with the shooter standing away from the animal with a direct line of sight of the muzzle and aiming position. With shotguns and low velocity pistols, the muzzle must be positioned close to the animal but not touching the head to avoid animal-based movements interfering with the correct positioning of the shot or bursting of the barrel. High-powered rifles, with greater velocities, should only be used from a suitable distance, in an outdoor setting with a safe background (Humane Slaughter Association [HSA] 2014). The shot should angle towards the neck to ensure maximal damage to brainstem structures and so the bullet is retained in the neck, reducing the risk to the operators and spare rounds must be immediately available for cases of failures.

Accidents involving controlled atmosphere stunning with gas can occur when there is a gas leakage from the equipment or the stunning box. However, these situations can be prevented with a proper maintenance of equipment to avoid gas leakage, the use of gas monitors inside of closed rooms, use of ventilation or outdoor operation.

Most accidents were caused by lack of attention and incorrect performing of practices. These accidents could be associated with the large number of operators who had not received any form of training or orientation for on-farm killing methods (Dalla Costa *et al* 2019). Independently of the method used, training and education for the correct use of on-farm culling practices should be implemented by companies to avoid accidents, promote the correct use of the methods and to improve the welfare conditions of pigs on farms.

Animal welfare implications and conclusion

Several methods can be used for culling pigs on-farm. Despite much of the recent development and progress in commercial stunning, there has been relatively little development of on-farm culling methods for pigs. Even for the currently recommended methods there is limited scientific evidence to support their routine use. Table 7 (see supplementary material to papers published in *Animal Welfare*: https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material) compares advantages and disadvantages of the different on-farm culling methods for piglets and pigs with a focus on animal welfare and operator-related factors. Manual blunt-force trauma is currently the most widely used method for on-farm culling of piglets. However, as a method, it should be significantly refined or replaced by other more effective alternatives due to concerns about the variability between operators. Captive-bolt stunners can be an effective on-farm alternative as a one- or two-step culling method when stockpeople are properly trained. However, some improvements in bolt length and the appropriateness of cartridges according to weight class should be evaluated. Free bullet worked effectively for adult animals when it could be used in situations where other alternatives are not available. However, there is a high risk of accidents involving operators and bullets that ricochet and exit the head/neck. Electrical stunning performed with proper equipment and combined with a secondary procedure (bleeding, head trauma and cardiac compression) can be an effective method for all weight categories. However, stockpeople should be aware of the risk of accidents during application with wet floors, inadequate personal safety equipment and incorrect electrode

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placement. Home-made devices should not be used for electrocution due to the high risk of inadequate stunning, animal suffering and accidents with operators. The use of carbon dioxide as a culling method for pigs is still debatable due to animal welfare concerns regarding pain, aversion and breathlessness. Low atmospheric pressure, which is a new technique recently developed for poultry, shows promise for the pig industry. However, very little is known about its effectiveness or welfare impact on pigs and equipment is not at present available commercially for use on farms. The core concern with LAPS is the potential risk of pain caused by expansion of trapped gases in internal body cavities. Each method has its own strengths and weakness, their selection is dependent on the resources available, level of available training and the need for further research.

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