The Old School, Brewhouse Hill, Wheathampstead,
Hertfordshire AL4 8AN, UK
www.ufaw.org.uk

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Assessment of key parameters for gunshot used on cattle: a pilot study on shot placement and effects of diverse ammunition on isolated cattle heads

KJ Schiffer*†, SK Retz†, U Richter†, B Algers‡ and O Hensel†

† University of Kassel, Faculty of Organic Agricultural Sciences, Department of Agricultural Engineering, Nordbahnhofstrasse 1a, 37213 Witzenhausen, Germany
‡ Swedish University of Agricultural Sciences, Faculty of Veterinary Medicine and Animal Science, Department of Animal Environment and Health, PO Box 234, 53223 Skara, Sweden
* Contact for correspondence and requests for reprints: schifferkj@gmail.com

Abstract

There have been many improvements regarding transport conditions, pre-slaughter handling, and captive-bolt stunning of cattle at commercial abattoirs, but many challenges still exist. Animals unaccustomed to human-animal contact, such as free-range beef cattle, may be especially difficult to handle on the day of slaughter. Shifting of the slaughter process from the abattoir to the animals' familiar environment could improve animal welfare at slaughter. In 2011, the German government passed an amendment allowing farmers to slaughter free-range cattle, on-farm, using a rifle. A proper stun is vital when employing this method but neither sufficient practical experience nor scientific knowledge are in place to allow this. Thus, this study aimed to examine shot placement and the effect of diverse ammunition by means of shooting at cattle heads, post mortem, with a rifle. Impact was assessed using brain tissue damage observed from skull dissections. Placing the shot frontally at the forehead resulted in severe brain damage significantly more frequently than targeting laterally. A precise frontal shot, utilising both large and small bore calibres, caused severe brain damage that would almost certainly have led to immediate unconsciousness and death. One of the small bore calibres caused minimal brain damage apart from the trajectory. However, this was the only calibre not passing straight through. Due to the fact that the bullet remains within the skull, thus transferring all of its energy to the skull and brain, the impact of this calibre on the brain would also be expected to be rapidly fatal. A projectile that does not exit the skull would also be advantageous as regards safety.

Keywords: *animal welfare, brain damage, cattle, gunshot, slaughter, stunning*

Introduction

Difficulties with standard cattle slaughter

The last few decades have seen many improvements in transport conditions, pre-slaughter handling, and stunning and bleeding of cattle at commercial abattoirs (Fischer 1994; Grandin 1998, 2006, 2012; Atkinson & Algers 2007, 2009). Nevertheless, concern remains regarding animal welfare during the slaughter process (Wernicki *et al* 2006; Hartung & Springorum 2009; von Wenzlawowicz *et al* 2012; Atkinson *et al* 2013). Whilst long road journeys can lead to habituation (Gebresenbet *et al* 2012), situations of acute stress, such as separation from conspecifics or unfamiliarity with the environment, frequently occur at the abattoir itself (Terlouw *et al* 2012). In principal, the negative impact of pre-mortal stressors on meat quality is well-known, ie dark-firm-dry meat (DFD) in cattle, but significant losses to the meat industry caused by DFD are still common. In addition, bruising, lacerations or other superficial blemishes, due mostly to unsuitable transport conditions, can lead to carcases being downgraded (Jarvis *et al* 1996; Ferguson & Warner 2008; Algers *et al* 2009; Shen *et al* 2009).

Livestock unaccustomed to human contact, such as free-range beef cattle, may show heightened stress levels as a result of handling and transport processes on the day of slaughter when compared to dairy cows, for instance, which tend to be more used to human contact. A possible strategy for reducing stress in slaughter animals would be to shift the slaughter process from the abattoir to a more familiar environment for the animals, ie their pasture. Consequently, dead, as opposed to live, animals would be transported to the abattoir, where evisceration and further processing would take place. In the event of highly professional guidelines being implemented and strict control from responsible authorities, shooting would represent an humane and effective method of on-farm stunning and killing of cattle, drastically reducing pre-mortal stress (AVMA 2013; Schiffer *et al* 2013).

Legislative background of on-farm slaughter via gunshot

Within Europe, slaughter on-farm via gunshot remains a complex issue. Until very recently the technique was uncommon for commercial slaughter with application limited mainly to emergency euthanasia, on-farm culling, and disease control (Algers *et al* 2009; Anil & Lambooij 2009). On one hand, the European regulation (EC) No 1099/2009 (EC 2009) on the protection of animals at the time of killing, lists gunshot as permissible for "slaughter, depopulation, and other situations" for "all species" (Annex I, Chapter I, Table I). While, on the other, regulation (EC) No 853/2004 (EC 2004) on the hygiene of foodstuffs (Annex III, Section I, Chapter IV, 2b) states that only live animals may enter a slaughter plant. Until recently, national legislation in Germany has been equally ambiguous regarding slaughter via gunshot (BMJ 2012 [TierSchlV]; BMJ 2007/2011 [Tier-LMHV]). In November 2011, the German government passed an amendment (BMJ 2007/2011, Tier-LMHV, §12, Section 3) permitting on-farm slaughter of free-range cattle as long as transport time from farm to facility does not exceed 1 h and permission has been granted by the responsible regional public authority. Consequently, on-farm slaughter via gunshot is recognised legally as a method of stunning and killing in all situations as opposed merely to cases of emergency. However, no further statutory regulations, such as those that exist for the shooting of farmed game (BMJ 2012), have been determined as yet for the shooting of cattle.

Lack of background knowledge, safety concerns and aim of the pilot project

According to German law, the bullet must impact upon the animal's head and stun or kill it immediately (BMJ 2012). In practice, opinion is divided amongst marksmen in Germany as to both the appropriate ammunition to use and the shot location (frontal or lateral). Additionally, there is a paucity of scientific literature on the subject (AVMA 2013). Finnie (1993) investigated the neuropathological features of traumatic head injuries in 20 sheep caused by two different types of .22 calibre free bullets. These were lateral shots, placed at the temporal region of the skull. Millar and Mills (2000) examined the trajectories of .32 calibre free bullets in 15 horses. These shots were placed frontally, 25 mm above the crossing point of two lines between the medial canthus (inside corner) of the eye to the base of the contralateral ear.

Frontal shot placement was also considered optimal for captive-bolt stunning of cattle. Present recommendations suggest a spot at the intersection of two imaginary lines drawn from the lateral canthus (outside corner) or middle of the eye to the base of the contralateral horn (Anil & Lambooij 2009; Gilliam *et al* 2012). Kohlen (2011) recommended a spot even a little higher in order to increase the probability of impacting the crucial area around the brainstem, and to decrease the risk of merely destroying the frontal sinuses. Thus, the danger of regaining consciousness (before death occurs via de-bleeding) can be reduced. Depending on the size of the animal, captive-bolt weapons for stunning of cattle are usually operated with energies between 300 and 600 J and a relatively low speed of < 100 m s^{-1} (Algers & Atkinson 2007; Anil & Lambooij 2009).

Safety aspects during slaughter via gunshot are paramount (AVMA 2013). The AVMA guidelines for the euthanasia of animals (AVMA 2013) state, for example, that a gun should never be held flush to an animal. For frontal shots, we recommend the marksman being situated on an elevated platform or embankment, preferably out of sight of the animal, and at a height of 2–4 m, as opposed to being at ground level. This might also facilitate making contact with the head at an appropriate angle (which, as with captive-bolt stunning, is generally considered to be approximately 90°) in frontal shots at cattle. The importance of maximum shooting accuracy cannot be over-stated. In addition, a backstop behind the animals, for example a sand wall, ought to be mandatory. Shooting within an enclosed area, such as a paddock, is strongly recommended instead of open pasture land where it might be impossible to find and reach an animal after a failed shot. In order to establish a calm ambience prior to shooting, no animal should be separated and any disruption of the social group should be avoided. The marksman should have a free choice, thus the individual animal standing in the most appropriate position can be shot, instead of the marksman having to wait until a particular animal is standing in a suitable position. According to prior consultation with the responsible veterinary office, on-farm ante mortem inspections for the whole group have to be undertaken in plenty of time (Retz *et al* 2013; Schiffer *et al* 2013).

Due to the fact that the shot is meant to kill the animal, power and calibre have to be of sufficient strength. However, shooting involves dangers and not only in cases of a failed shot or a ricochet but also the projectile (which still features a considerable amount of energy) passing straight through the cow's head. Therefore, ammunition supplying the requisite velocity and energy for a rapid death whilst also remaining within the skull of the targeted animal would substantially improve safety concerns.

The overall goal of this pilot project was to scrutinise slaughter of outdoor cattle via gunshot and ascertain whether it could become a professional, reliable and easily controllable on-farm slaughter method. With respect to animal welfare, a proper stun quality is essential. Thus, we sought to address the following three questions:

- Is lateral targeting as reliable as frontal targeting;
- Which calibres cause severe brain damage that is likely to be sufficient for a proper stun; and
- Do any of the tested calibres remain within the skull instead of passing through?

The first experiment of our study focused on the first point whilst the second experiment looked at the following two.

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Table 1 Ammunition characteristics, shot localisation, and numbers per calibre that were employed for shooting at isolated cattle heads.

Calibre	Shot localisation	Bullet diameter (mm)	Bullet mass (g)	V_0–V_{100}* (m s^{-1})	E_0–E_{100}* (joule)	Type#	n
9.3 × 62	Frontal	9.3	18.5	695–600	4,470–3,360	pfb	4
.30-06 bionic yellow	Frontal	7.6	10.0	885–760	3,915–2,880	pfb	5
.30-06 bionic black	Frontal	7.6	10.0	885–760	3,915–2,880	db	6
.30-06 bionic black	Lateral	7.6	10.0	885–760	3,915–2,880	db	6
.30-06 Barnes	Frontal	7.6	10.9	850–790	3,940–3,360	db	2
.22 Hornet	Frontal	5.6	2.9	770–550	865–460	pfb	5
.22 Hornet	Lateral	5.6	2.9	770–550	865–460	pfb	5
.22 Magnum	Frontal	5.6	2.6	580–400	440–210	pfb	4

V_0 and E_0 describe the velocity/energy of the projectile at the muzzle. V_{100} and E_{100} describe the velocity/energy of the projectile after 100 m. Velocity and energy according to the producers/re-sellers, no exact values. # Type means part fragmenting bullet (pfb) or deformation bullet (db).

Materials and methods

Sample structure and statistics

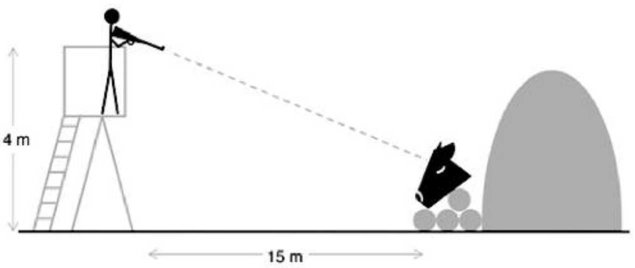
After consultation with the relevant veterinary state authorities, isolated post mortem heads were collected at two commercial abattoirs in northern Germany. The cattle originated from two farms rearing all-season outdoor cattle, located close to the abattoirs. The animals were stunned electrically (head and cardiac arrest; see TVT 2007) before slaughtering, which meant their heads remained intact and with no bullet hole from the stunning process. The influence of this electrical stunning on the brain tissue was not evaluated in the present study. The stored heads were deep frozen and allowed to thaw at room temperature for approximately 48 h before use (see *Discussion*). The carcases were meant for commercial sale and, therefore, both the co-operating farmers' herd management and their marketing activities limited sample collection.

Altogether, 37 heads were collected, of which 33 were German Angus and four were Galloway (these four were shot with the .22 Magnum ammunition). Of the German Angus, 14 were bulls and 19 were females. All the Galloway cattle were steers. The median age was 20 (± 20) months, ranging from 7–129 months. Due to the heterogeneity of the sample structure, the small number of heads available for the experiments and the relatively high number of variations employed, a mainly descriptive evaluation of the data was carried out. Pearson's correlations were calculated for the relationship between skull thickness at the entry wound and age and sex, respectively, and Fisher's exact test for the relationship between brain damage and shot position (both via SPSS software). The level of significance was set at $P < 0.05$.

Ammunition

The different calibres and types of ammunition (Table 1) were chosen based on the co-operating marksmen's recommendations and their prior experiences regarding both hunting and on-farm shooting of live cattle. All were accredited hunters according to German law.

Figure 1



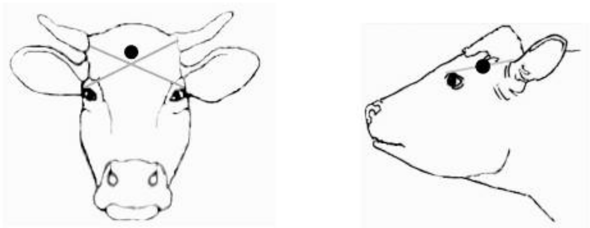
The experimental set-up. The marksman was situated on a raised hide, and the animal's head placed on sandbags with a backstop behind.

Shooting

The marksman, using a long rifle, was situated on a raised hide, approximately 4 m above the ground (Figure 1). The animal's head was placed on the ground, on sandbags in front of a backstop, at a range of *circa* 15 m. The setting was reflective of the on-farm conditions in which outdoor cattle slaughter via gunshot would preferably occur (Schiffer *et al* 2013). Shooting at the isolated heads was performed with permission from the responsible regulatory and veterinary state authorities. On the four days of shooting, the weather was calm and it was therefore assumed that the external ballistics were not affected by wind or precipitation. For logistic reasons, each shooting day was linked to the use of a certain weapon and related types of ammunition. Therefore, it was not possible to blind the participating veterinarian as to skull dissections and brain damage evaluation relative to the calibre employed.

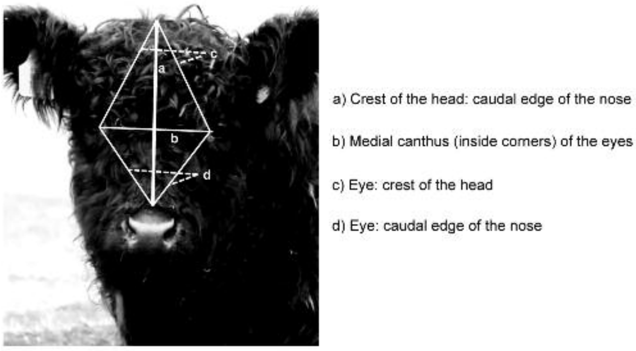
It was supposed that optimal frontal shot placement would be consistent with present recommendations for captive-bolt stunning. The assumed optimal position for a frontal gunshot at cattle is shown in Figure 2 (left). Before the shot, the target location was marked with a paint-dot sprayed on each head.

Figure 2



Assumed optimal position for frontal shots (left) and lateral shots (right), (modified according to http://de.wikipedia.org/wiki/Schlachtung#mediaviewer/File:Bet%C3%A4ubung.jpeg).

Figure 3



Assessment of anatomical measures (modified according to Kohlen 2011).

Table 2 Measurements of the cattle heads employed in this study (n = 37).

	Mean (± SD)	Coefficient of variation (%)
Crest of the head: caudal edge nose	41.5 (± 2.5)	6
Medial canthus eyes	18.2 (± 1.5)	8
Eye: crest of the head	23.2 (± 1.7)	7
Eye: caudal edge nose	22.5 (± 1.8)	8
Skull thickness at entry wound*	1.5 (± 0.5)	34

* In frontal shots, ie n = 26.

For lateral targeting, the authors made use of anatomical knowledge of the participating veterinarian. The assumed optimal shot position (Figure 2, right) was at a point approximately 5 cm short of the upper edge of the base of the external ear in the direction of an imaginary line between ear and eye. A perpendicular angle of impact was assumed to be most favourable in order to hit the brain properly.

Dissection

Each skull was dissected and brain damage analysed by an authorised veterinarian, with extensive research experience in cattle stunning and the assessment of animal welfare during slaughter. Firstly, the skull was fixated onto an adapted bench vice and the position of the entry wound identified by measuring deviation from the marked optimal shot position. Subsequently, anatomical measures (modified according to Kohlen 2011) of each head were determined from Figure 3: a) the length between the crest of the head and the caudal edge of the nose; b) the length between the medial canthus (inside corners) of the eyes; c) the length between the inside corner of the eye and the crest of the head; and d) the length between the inside corner of the eye and the caudal edge of the nose.

The coat was removed and the diameter of the entry wound determined. According to Finnie (1997), tissue specific gravity plays the most significant role in terms of retarding influences on a bullet and, thus, bones have the greatest impact when an animal is shot. In our investigation, skull thickness was measured at the entry wound. For measuring the angle of impact of frontal shots, 0° was determined in a rostral (nostrils) and 180° in a dorsal (crest) direction. Regarding ear shots, 0° was determined in ventral direction (down) and 180° in dorsal direction (crest). The angle of impact was determined by carefully introducing a slim sounding rod into the bullet hole, following the trajectory until the exit hole (if bullet passed through the skull) or the bullet itself (if it remained within the skull) could be detected. The depth of penetration of the bullet was determined at this stage. Subsequently, a square of the skullcap (calvarium) was removed by using an electrical saw as well as a rubber mallet and a chisel. The brain was carefully removed from its cavity if procurable (some cases revealed obliteration of the brain tissue without any ordinary anatomical structures left).

Brain damage was evaluated by visual examination and defined as 'severe' when the area of the brainstem, which is considered as the most crucial area for a proper stun (Algers & Atkinson 2007; Kohlen 2011), was disrupted, and as 'marginal' when only cerebrum and/or cerebellum or minor parts of the brainstem were destroyed. 'Severe' brain damage was deemed sufficient for a proper stun. Following dissection, all the heads were disposed of in an appropriate way (serious risk material) at the abattoirs.

Experiments

The first experiment focused on the comparison of frontal and lateral shots. One large and one small bore calibre were used for shooting at the heads of German Angus cattle (n = 22, mean age = 18 [± 9] months). Six heads each were shot, lateral or frontal, with a large bore (.30-06 bionic black) and five heads, lateral or frontal, with a small bore (.22 Hornet).

The second experiment dealt with assessing the effectiveness of different calibres as regards brain damage and determination of suitable ammunition that causes 'severe' brain damage while remaining within the head. Four different large bores (9.3 × 62, .30-06 bionic yellow, .30-06 bionic black, .30-06 TTSX; total n = 17) and two small bores (.22 Hornet and .22 Magnum; total n = 9) were tested using frontal shots. Due to the limited number of heads available for the whole study (total n = 37), the frontal shots of the first experiment (.30-06 bionic black, .22 Hornet, total n = 11) were also included in the assess-

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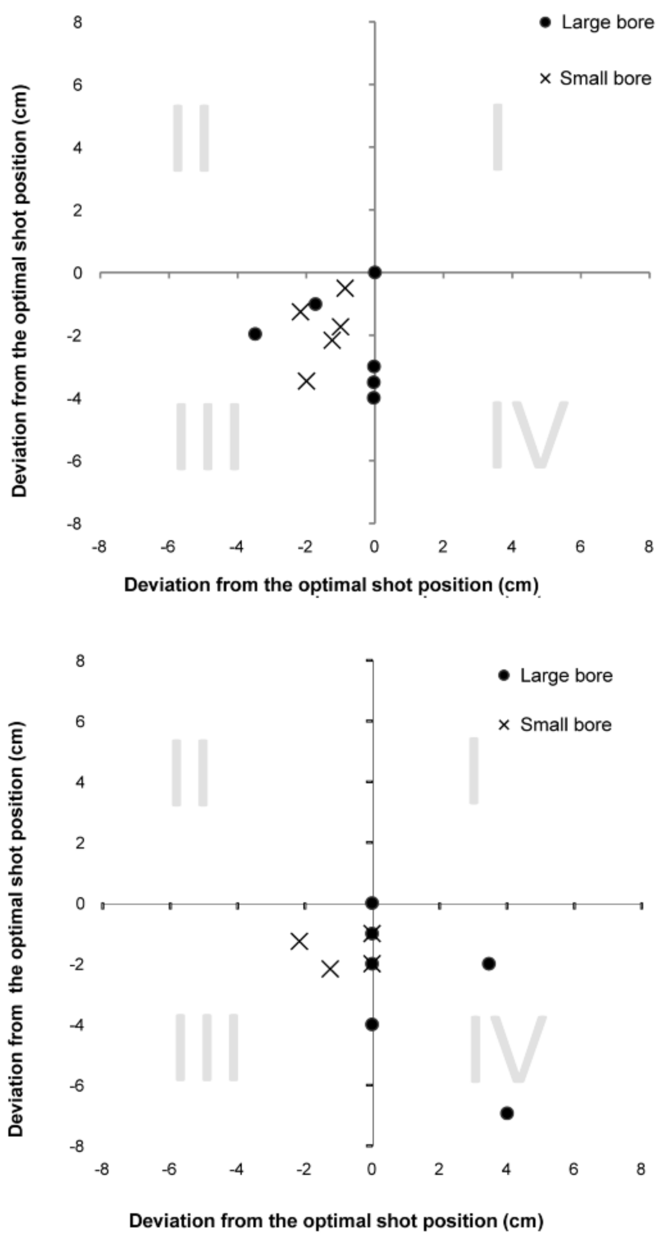
Figure 4



Deviation (cm) from the assumed optimal shot position located at the zero-point of the co-ordinate system: frontal shots (upper) and lateral shots (lower), shot with a large or small bore calibre, respectively.

ments of the second experiment. A larger variety of large bores were tested than small, because large bores were the most common calibres among German farmers already using the gunshot method on outdoor cattle.

Results

Sample structure

Differences in head anatomy were marginal (Table 2). Only skull thickness (frontal shots) varied substantially, as the coefficient of variation reveals. However, no significant correlation (SPSS, Pearson) could be detected between skull thickness and age or sex of the animals used in this study.

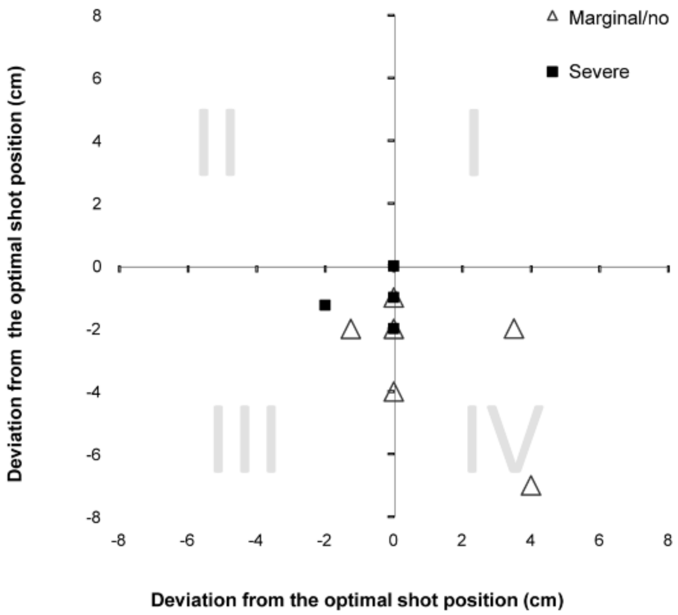
Frontal versus lateral targeting

Shot deviation and angle of impact

Converted into a co-ordinate system with the zero-point as the ideal shot position, all of the eleven frontal shots were placed in the third quadrant or at the y-axis (Figure 4, upper). The maximum deviation from the assumed optimal frontal shot position was 4 cm. The average angle of impact of the frontal shots was 112 (± 4)°.

The lateral shots (total, n = 11) were placed in the third and fourth quadrants (Figure 4, lower). One shot localisation (x-axis = 0; y-axis = 2) was found in three heads (twice with small bore and once with large bore). Another shot localisation

Figure 5



Severity of brain damage after lateral shots ('marginal/no' or 'severe'). The localisation of the symbols shows the deviation of each shot from the assumed optimal shot position that is at the zero-point of the co-ordinate system (see Figure 4, lower).

was found in two heads (x-axis = 0; y-axis = 1). All lateral shots were placed perpendicular (90 [± 1.5]°) to the head.

Brain damage

Examining the brain after frontal shots revealed that all six of the large bore (.30-06 bionic black) and all five of the small bore (.22 Hornet) projectiles (Figure 4, upper) caused 'severe' brain damage that was supposed sufficient for rapid unconsciousness or death in live cattle. All of these eleven frontal shots caused a shot straight through with an exit wound close to the spinal canal.

Examining the brain after lateral shots (same calibres) revealed that only two of six large bore shots and two of five small bore shots caused 'severe' brain damage. Two shots caused 'marginal' brain damage and five shots passed completely below the brain and did not inflict any brain damage.

Placing the shot at the frontal position resulted in 'severe' brain damage significantly more frequently ($P < 0.01$) than placing the shot at the lateral position.

Six of the seven failed lateral shots were situated within a 4-cm radius of the assumed optimal lateral shot position but, unlike frontal shots within this radius, they did not cause 'severe' brain damage (Figure 5). One localised position (x-axis = 0; y-axis = 2) was found in three heads (twice with small bore and once with large). In one of these shots, the brain damage was 'severe' but in the second the brain was not hit at all — even though both were shot with the same calibre (small bore) and revealed almost the same head measurements, same sex (female) and same age (one year). The third shot with the same co-ordinates was also a failed shot (large bore, smaller head). A further lateral shot localisation was found in two heads (x-axis = 0; y-axis = 1). The brain damage was 'severe' when shot with a large bore and 'marginal' when shot with a small bore. The head measurements of these animals were almost the same, but the head shot with a small bore originated from an animal one year older. Nine out of eleven lateral shots remained in the head. The mean (± SD) penetration depth of these shots was 13.7 (± 2.1) cm.

Brain damage caused by different calibres

All five frontal shots using the small bore (.22 Hornet) and 16 out of 17 frontal shots with four different large bores caused 'severe' brain damage (Figure 6). In contrast to that, the other small bore used in this study (.22 Magnum, n = 4), did not cause any brain tissue damage apart from the trajectory of the bullet itself (Figure 7). The mean angle of impact of the frontal shots in the second experiment was 112 (± 11)° (n = 26).

Passing shot

All frontal large bore shots (n = 22) and all frontal shots of the small bore .22 Hornet (n = 5) passed through the skull with an exit wound in the area around the spinal canal. In the case of the strongest large bore used in this study (9.3 × 62, n = 4), small fragments of the bullet also left the skull. In contrast, all frontal shots of the other small bore .22 Magnum (n = 4) remained in the head. The penetration depth of the .22 Magnum bullet into the cranial cavity was 12.1 (± 1.9) cm. Residues of the projectile were found in the occipital bone at the base of the cranial cavity (Figure 8).

Discussion

Frontal versus lateral targeting

All frontal shots from the first experiment were located in the third quadrant (Figure 4, upper). Due to skull symmetry, it can be assumed that frontal shots within the same radius of 4 cm are equally efficient as shot placement in the fourth quadrant. It is also likely that shots within this

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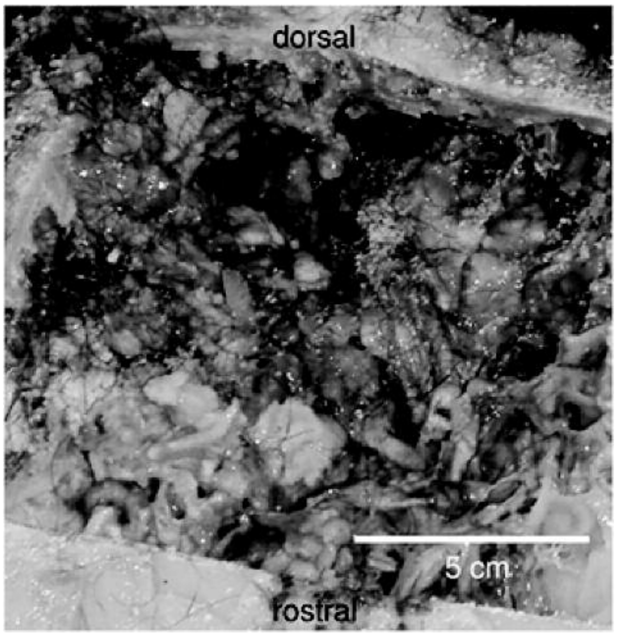
radius would cause substantial brain damage if situated in the first and second quadrant, building a target area with a radius of 4 cm. However, unless confirmed by further research, the authors recommend a smaller target area of approximately 2-cm radius for gunshot placement, such as that recommended for captive-bolt stunning (Ilgert 1985; Atkinson *et al* 2013).

Shooting laterally instead of shooting at the frontal position was reported as an efficient way of inflicting sufficient head wounds in sheep by a .22 calibre firearm (Finnie 1993). From a range of 3 m, ten sheep were each shot with a high velocity round-nosed bullet and a lower velocity hollow-point bullet, respectively. The bullets caused a right to left transverse wound to the brain through the temporal lobes. These shots passed right through with a comparably large exit wound, when using the high velocity bullet, or the bullet remained inside the head without an exit wound when using the lower velocity bullet. When shooting laterally at cattle, nine out of eleven shots remained within the head, even four out of six large bore shots. However, 'severe' brain damage occurred significantly less frequently when shooting laterally at cattle heads compared to frontal shots. Differences between lateral shots which failed to hit the brain and frontal shots with the same length of deviation from the assumed optimal shot position, which still caused 'severe' brain damage, indicate that the danger of a failed shot might be higher for a lateral than a frontal shot. The optimal target area for lateral shots appeared to be not only smaller (which necessitates even greater skills as a marksman) but also more diffuse than that for frontal shots. This became obvious when several of the lateral shots, with almost the same angle of impact, hit the same co-ordinates but caused highly variable brain tissue damage. Possible reasons might include anatomical structures (wider suitable contact surface of the brain when addressed frontally) or slight individual differences in the brain localisation. A slightly more acute angle of impact (< 90°) might have benefited the trajectory of lateral shots. In live cattle, this might be achieved by shooting from the ground instead of from an elevated platform, which is, however, not to be recommended due to substantial safety concerns. In general, further investigations should clarify if the assumed optimal shot position for lateral shots needs to be placed further into a dorsal (upwards) direction, which might decrease the danger of the bullet passing beneath the brain.

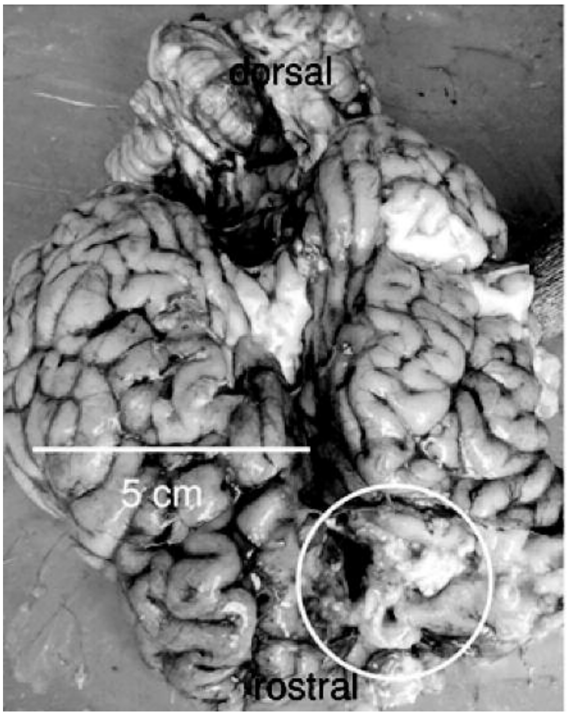
Millar and Mills (2000) reported considerable variation in brain damage with frontal gunshots in 15 horses, even though in their experiments the point of entry was virtually the same for every shot. They suggest the reason for this was individual variation in the geometry of the head and, further, deviations in the alignment of the weapon. In the current study, however, the frontal shots (n = 11) resulted in 'severe' brain damage even though the deviation from the optimal shot position was approximately 4 cm and the angle of impact (112 [± 4]°) was more obtuse than expected. Differences between the species and their anatomical structures might explain the divergent results.

Figure 6



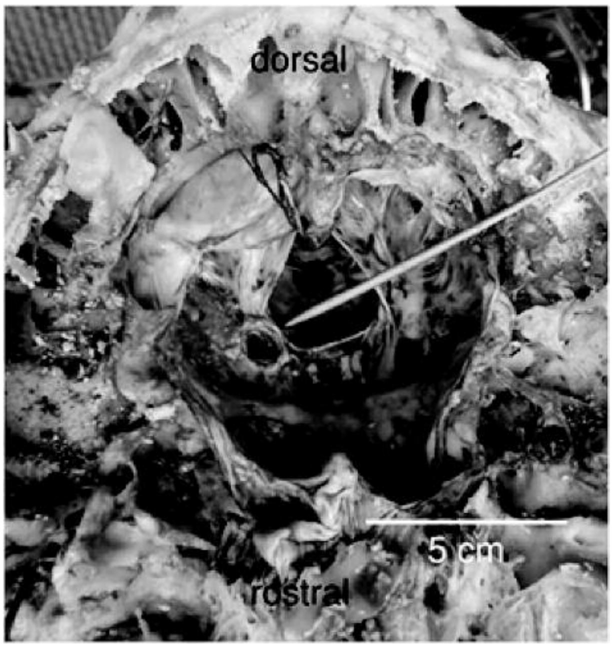
Top view of the cattle brain after a large bore shot (.30-06 bionic black): total destruction of the brain tissue.

Figure 7



Top view of the brain after a small bore shot (.22 Magnum): almost no destruction of the brain tissue except from the trajectory of the bullet (marked in the white circle).

Figure 8



Top view of the cranial cavity after removal of the brain tissue. The projectile (.22 Magnum) remained in the occipital bone, to the left below the sounding rod.

Brain damage caused by different calibres

The mean angle of impact in this experiment was 112 (± 11)° (n = 26) and more obtuse than expected. Because of the anatomical structure of the brain and its relatively 'flat' caudal direction concerning the brainstem, it was supposed that a less obtuse, or even right angle, may increase the probability of hitting the brainstem. Further research is required to clarify the deviations in the angle of impact that are tolerable. However, with the exception of all calibre .22 Magnum shots (and one failed shot), all caused 'severe' brain damage as shown in Figure 6. No distinct differences in the related brain damage could be detected regarding the different calibres chosen, apart from the .22 Magnum. These projectiles barely produced any brain tissue damage apart from the trajectory of the bullet itself (Figure 7). Nonetheless, we consider that the .22 Magnum calibre could be suitable for use on live cattle, for the reasons given below.

Passing shot

The issue of bullets either passing through or remaining inside the head of cattle needs thorough consideration as it is yet to be looked at in sufficient detail. In the present study, only the .22 Magnum projectiles remained within the animal's head — in contrast to all other projectiles employed for frontal shots, even the other small bore calibre (.22 Hornet), which was not expected to pass through the skull following frontal shots, either. The absence of the projectile passing through the skull is probably due to the relatively low E_0 of the .22 Magnum projectile (440 J), which is similar to common captive-bolt cartridges. This is over ten times less than the E_0 of the large bore 9.3 × 62 (4,470 J), also almost ten times less than the .30-06 calibres (3,915 J), and around half the energy of the other small bore calibre (.22 Hornet, 865 J). Atkinson and Algers (2007) reported successful use of 9.6 calibre free projectiles for larger bulls. In the current study, the use of such extremely large bores appeared not to be necessary for traditionally relatively small German Angus or Galloway cattle. All three of the tested .30-06 calibres penetrated the skullcap (total n = 13) and caused (except for one failed shot) 'severe' brain damage in a similar manner to the largest one (9.3 × 62, n = 4). Blackmore (1985) studied the energy requirements necessary for the penetration of isolated heads of various species and found even 165 J suitable for most classes of stock including beef cattle. The wide range of recommended energies highlights the need for further research into the efficiency of gunshot for humane and safe slaughter purposes.

Regarding the question of a passing shot and the .22 Magnum projectiles, which remained within the cranial cavity, wound ballistics, as described by Di Maio (1999), need to be taken into account: when a live organism is shot, the severity of the wound is determined not only by the amount of brain tissue damage but also the so-called temporary cavity (this is not the case in the post mortem heads used in the current study). The temporary cavity is created by surrounding tissue flinging outwards radially from the trajectory, which is crucial to the total damage of the brain. A temporary cavity will be much bigger than the diameter of the projectile. It only exists for 5 to 10 ms, but determines the permanent wound track. The size of the temporary cavity and, thus, the severity of brain damage is a result of the amount of energy lost in the tissue rather than the total energy possessed by the bullet. For example, a projectile A, with more kinetic energy than projectile B, causes less severe brain damage than B because A exits the body. A projectile that does not pass through the cranial cavity expends its energy while fracturing the skull and is then captured in the cranium. This implies that the whole energy of the projectile remained within the cranial cavity and impacts wound formation. Thus, the likelihood of rapidly inflicting fatal haemorrhage is high (Finnie 1997; Di Maio 1999). Further, Anil and Lambooij (2007) related the temporary cavitation effect to the velocity of the projectile and suggested that it occurs at > 300 m s^{-1}. This applies to the .22 Magnum projectile (V_0 = 580 m s^{-1}), but not to customary captive-bolt stunning (< 100 m s^{-1}). For captive-bolt stunning, the maximum penetration depth is determined by the length of the bolt. Depending on the device (common bolt lengths are 8 or 12 cm) and thickness of skin and hair, the brainstem might not even be inflicted at all (Kohlen 2011). In contrast, a large bore projectile passing through the skull might destroy the brainstem anyway. Yet, the instance of a shot remaining within the skull, such as the .22 Magnum projectiles, can also see full penetration of the brain, with the projectile remaining at the base of the cranial cavity, plus the temporary cavitation effect. Thus, we suggest that a precise frontal shot from a .22 Magnum should be effective for causing an immediate stun or kill of small- or medium-sized cattle.

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Regarding safety concerns, the risk of injuring either people or conspecifics is minimised when a projectile is used that does not have sufficient momentum to pass through the head (Blackmore 1985). Moreover, a projectile remaining within the cranial cavity would reduce concerns regarding the emission of bullet fragments upon impact of edible tissue. However, the properties of suitable, lead-free ammunition for slaughter purposes of cattle require further investigation.

Sample structure

As a result of the authors' reliance on the herd management of the co-operating farms, the sample structure was not as homogeneous as would have been preferred. Males, females and castrated males of very different ages as well as two different breeds were employed in this study. Yet, differences in the head anatomy were marginal as shown in Table 2; with the exception of 'skull thickness at the entry wound', which revealed a far greater coefficient of variation than all other head parameters. This is probably due to taking measurements at the entry wound as opposed to a fixed position. In this study, no significant correlation was found between skull thickness and age or sex of the animals, though others have noted findings about thicker skulls in bulls (eg Atkinson *et al* 2013). However, one additional head of a 34 month old water buffalo bull was shot with a small bore (.22 Hornet). Even though the thickness of the skull was 7 cm and, thus, more than four times thicker than that of all the other cattle shot in our study, the projectile did enter the cranial cavity and even passed through. This outcome was not representative, but suggests that the high coefficient of variation in skull thickness was negligible for the purposes of this special study.

Our study would have benefited from blinding the person evaluating the dissections to the calibres used and this should be done in any future studies. Also, it would have been helpful if additional dissections had been made of frozen and thawed heads that had not been shot. Finally, the results presented here need to be considered in light of the possibility that the freezing and thawing of the heads, could have emphasised or disguised brain damage.

Type of projectile

Free projectiles provide optimised energy transfer by deforming and/or fragmenting when hitting the target (Anil & Lambooij 2009). Fragmentation of free bullets and the secondary wound tracks caused by the fragments of the bullet enhance brain damage creating the major difference from a penetrating captive-bolt pistol, in terms of efficacy (Finnie 1997). As shown in Table 1, different types of projectiles were chosen but no preferences concerning either fragmentation or deformation could be derived from the present study. Neither was it possible to distinguish between different projectile styles, such as semi-jacketed, homogeneous or lead-free, nor to focus on the construction of the projectiles, such as soft or hollow point. Generally, hollow-point projectiles provide an optimised transfer of energy without the danger of over-penetration (AVMA 2013). Further research, also including computed tomography and more standardised instead of field conditions, is necessary to gain valid data concerning wound ballistics and those specialised features of ammunition (AVMA 2013).

EC Regulation

The key parameters as listed in the EC Regulation No 1099/2009 (EC 2009, Annex 1, Chapter 1, Table 1) for the analogous slaughter method 'firearm with free projectile' have been taken into consideration as far as possible: (these are 'position of the shot', 'power and calibre of the cartridge' and 'type of the projectile'). On one hand, the authors' aim of evaluating the wide range of possible shot variations was reached and, in terms of the key parameters 'position of the shot' and 'power and calibre of the cartridge', preliminary results could be concluded. On the other, though, as regards the 'type of the projectile', no preferences could be derived.

In contrast to other methods listed in this regulation, neither a stun-to-stick interval nor the remark 'simple stunning' can be found for gunshot. Gunshot can be considered as a method for killing rather than a traditional method for stunning, such as captive-bolt stunning. However, in order to promote animal welfare and standards of hygiene, debleeding via chest-stick should be directly applied.

Animal welfare implications

Slaughter by gunshot must only be carried out by highly skilled marksmen to ensure high reliability. This being the case it is a method that has the potential to promote a high standard of animal welfare at slaughter.

Conclusion

Frontal versus lateral targeting

Lateral shots at isolated cattle heads were not as successful as expected and, based on these data, we recommend frontal shots at cattle. However, a more optimal shot position for lateral shots may exist and should be further investigated.

Brain damage

All of the calibres tested can be preliminarily recommended for precise frontal shots at small cattle. All caused 'severe' brain damage, with the exception of the .22 Magnum calibre. Nonetheless, due to different and very effective wound ballistics, this calibre was also regarded as suitable for causing a proper stun.

Passing shot

In frontal shots, all of the tested calibres passed through, except for shots taken with the .22 Magnum calibre, which remained within the skull. As regards safety, the .22 Magnum calibre seems the most favourable for shooting relatively small cattle breeds such as the Galloways employed in this study.

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