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Animal Welfare 2016, 25: 347-353
ISSN 0962-7286
doi: 10.7120/09627286.25.3.347

Evaluation of brainstem disruption following penetrating captive-bolt shot in isolated cattle heads: comparison of traditional and alternative shot-placement landmarks

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Abstract

Currently recommended landmarks for captive-bolt euthanasia of cattle often result in failure to penetrate the brainstem. The purpose of this study was to evaluate the ability to disrupt the brainstem by placing the shot at a higher position on the head. Intact heads from euthanased animals or natural mortalities were used for this study. Heads were grouped as adult (> 2 years), young (6–24 months) and neonate (< 1 month) and randomly assigned to either the LOW group (the intersection of two lines drawn from the medial canthus to the top of the opposite ear) or the HIGH group (midline halfway between the top of the poll and an imaginary line connecting each lateral canthus). Each head received a single shot from a CASH penetrating captive bolt with bolt length and power load selected based on manufacturer's recommendations. Computed tomography images of each head were evaluated independently by two veterinary radiologists. Brainstem disruption was assumed to occur if the bolt passed caudal to the presphenoid bone and deep to the third ventricle and was within 1.5 cm of midline. Brainstem disruption occurred in 16/18 adult HIGH and 7/14 adult LOW heads, 13/16 young HIGH and 11/19 young LOW heads, and 11/11 neonate HIGH and 14/14 neonate LOW heads. The higher shot location landmarks used in this study increased the probability of disrupting the brainstem when adult cattle were shot with a penetrating captive bolt which should reduce the risk of regaining sensibility. Reliable brainstem disruption is a precondition for considering penetrating captive bolt as a single-step euthanasia method. Further research is needed to determine if this method will reliably ensure a humane death.

Keywords: *animal welfare, brainstem, captive bolt, cattle, euthanasia, shot placement*

Introduction

Humane euthanasia of cattle often presents significant challenges for veterinarians and cattle producers. Cattle in need of euthanasia may be found in a wide variety of circumstances, many of which can make humane euthanasia difficult to achieve. These challenges may be greatest when a large number of animals need to be euthanased in a short period of time, such as might occur with a natural disaster or epidemic animal disease outbreak.

Based on the recommendations from the American Veterinary Medical Association (AVMA), there are three approved methods of euthanasing cattle (AVMA 2013). Intravenous injection of a barbiturate, such as pentobarbital sodium, is commonly used to euthanase a variety of animal species. While this method is effective for cattle, it is only available to veterinarians and can result in dangerous environmental residues if carcases are not disposed of properly. Physical disruption of the brain via gunshot is effective and readily available in many locations. While effective and potentially applicable to a mass depopulation setting, gunshot requires skilled personnel and has significant safety concerns. Firearm use is also subject to legal restrictions in some areas. The final approved method of euthanasia is physical disruption of the brain via a captive-bolt device.

Captive bolts are used routinely for stunning animals prior to slaughter and are available in penetrating and non-penetrating configurations. Penetrating captive bolts (PCB) are used most commonly for cattle. These devices render the animal unconscious via concussive forces generated when the bolt strikes the skull (Daly & Whittington 1989; Gregory & Shaw 2000). The bolt, often accompanied by bone fragments, penetrates the brain causing additional concussion, physical destruction of brain tissue and haemorrhage within the cranial vault. Although the loss of consciousness is instantaneous, it may not be permanent (Grandin 2002). In a slaughter setting, animals are quickly exsanguinated after being stunned, reducing the risk of an animal regaining sensibility and suffering pain. The potential for some animals to regain sensibility has led to the recommendation that a secondary step be applied to ensure death when animals are euthanised with a captive bolt (Finnie 1997; American Association of Bovine Practioners [AABP] 2013; AVMA 2013). Currently recommended options include exsanguination, pithing, or intravenous injection of a saturated salt solution, such as potassium chloride. When a single animal or small group of animals needs to be euthanased, application of one of these secondary steps is relatively easy. In the event that a large number of animals need to be euthanased or when animals are difficult to access, such as during a vehicular accident, effective application of one of these secondary steps can be difficult or even potentially dangerous to the operator. The need exists for a euthanasia method that has the advantages of a captive bolt but does not require the application of a secondary step to ensure death.

If a PCB can physically disrupt the brainstem in addition to causing concussion and disruption of the cerebral cortex, the risk of regaining sensibility should be reduced. Various levels of consciousness are controlled by both the cerebral cortex and brainstem (Gregory & Shaw 2000). Specifically, the state of consciousness is controlled by the ascending reticular activating system located within the brainstem (de Lahunta & Glass 2009; Smith *et al* 2009). Physical penetration of this area by the bolt or by bone fragments should increase the likelihood of permanent loss of consciousness.

In order for a PCB to directly penetrate the brainstem, the shot must be placed accurately relative to external anatomic landmarks and the bolt must achieve adequate penetration to reach the brainstem. To achieve maximum penetration, the PCB must be held in firm contact with and perpendicular to the skull. Traditional shot placement recommendations for captive-bolt use in the United States have stated that the shot should be placed at the intersection of two imaginary lines drawn from the medial canthus of the eye to the opposite horn or top of the opposite ear (Lambooy 1981; AABP 1999; Gardner 1999). The World Organization for Animal Health recommends a higher, or more caudal, shot placement described as the intersection of two imaginary lines drawn from the lateral canthus of each eye to the opposite horn or opposite ear (OIE 2015). More recently, the shot placement recommendations in the US have been modified to be consistent with the position described by the OIE (AABP 2013; AVMA 2013).

In a recent study, the authors compared the likelihood of physically penetrating the brainstem utilising these two shot placements in bovine cadaver heads (Gilliam *et al* 2012). This study demonstrated that disruption of the brainstem is more likely when the higher, or more caudal, shot placement is used but that the bolt path was still too far rostral in some heads to directly penetrate the brainstem. Based on clinical observation, the authors believe that the risk of missing the brainstem increases as the size and length of the head increases. This seems to be particularly true in some dairy breeds, animals with Brahman influence and animals with large horns. The authors hypothesise that an alternative set of landmarks that accounts for variations in head size or shape would increase the likelihood of penetrating the brainstem.

The purpose of the study reported here was to investigate the ability to physically disrupt the brainstem in bovine cadaver heads using a captive-bolt system designed specifically for on-farm euthanasia of a variety of livestock species when a single shot is placed utilising landmarks that account for variations in head size or shape.

Materials and methods

Study animals

Intact heads were collected as they became available, regardless of breed, sex, or age, from natural mortalities or cattle that were euthanased for reasons unrelated to the study. All euthanased cattle were euthanased via pentobarbital injection in order to preserve the skull and brain for the purposes of the study. In total, 92 heads were obtained and frozen until use. Heads were grouped according to recorded age or dentition: 32 Adult (> 24 months), 35 Young (6–24 months), and 25 Neonate (< 1 month of age). Both sexes and a variety of breeds (both beef and dairy) were included in the study, however, numbers were too small to allow any meaningful comparisons within a specific sex or breed group. A total of 92 heads were utilised for this study.

Captive-bolt equipment

The CASH Dispatch Kit (Accles and Shelvoke, Sutton Coldfield, UK) was used in this study. This system accommodates penetrating bolts of various lengths including an extended bolt that is longer than that of most traditional captive-bolt devices. In addition to the penetrating bolts, the kit includes a non-penetrating muzzle attachment, allowing the bolt type to be matched correctly with the type of animal being euthanased. Five power loads of various strengths are also available to allow matching of the appropriate power load to the animal being euthanased. The bolt length and power load combinations utilised for each group in this study were based on the manufacturer's recommendations. Specifically, heads from adult cattle were shot with the extended bolt and orange power load. Those from young cattle were shot with the standard length bolt and blue power load and those from neonatal cattle were shot with the standard length bolt and yellow power load. Specifications of each of these bolt and power load combinations are provided in Table 1.

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Shooting procedure

Prior to shooting, each head was allowed to thaw at room temperature for at least 24 h. Heads were randomly assigned by coin toss to one of two shot placement groups. The LOW group received a single shot at the intersection of two lines each drawn from the medial canthus of the eye to the centre of the opposite horn or top of the opposite ear in polled heads. The HIGH group received a single shot at a point on the midline halfway between the top of the poll and a line drawn from one side to the other between the lateral canthus of each eye (Figure 1). For both groups, lines were placed physically on each head using elastic cord with hooks attached to each end. The appropriate shot location was then marked with paint and the cords removed prior to shooting. For the shooting procedure, each head was restrained in a vice (Rockwell Jawhorse®, Positec Tool Corporation, Charlotte, NC, USA) with the jaws modified to increase the stability of the head.

Computed tomography scanning

Each head underwent computed tomography (CT) scanning to determine the location of the bolt path within the skull and/or brain. Images were obtained using a bone algorithm at 2.5-mm slice thickness at 120 kV and 275 mA. Images were reconstructed using a detail algorithm at 1.3-mm slice thickness. Sagittal reformats were obtained at 0.6 mm.

Evaluation of CT images

Independent evaluation of the CT images was performed by two board-certified veterinary radiologists who were blinded to shot placement groups. The radiologists evaluated both sagittal and transverse images of each head and were asked to determine if the brainstem was physically disrupted according to the following parameters: i) did the bolt path pass caudal to the presphenoid bone (sagittal view); ii) did the bolt path penetrate deep to the level of the third ventricle (sagittal and transverse views); and iii) was the bolt path within 1.5 cm of the midline (transverse view) (Figure 2). The third ventricle was chosen as a landmark because it is located between the cerebral cortices and brainstem and could be readily identified in the CT scans. If all of these conditions were met, the shot was determined to have successfully disrupted the brainstem (result recorded as YES). If any of these conditions were not met, the shot was considered to have failed to disrupt the brainstem (result recorded as NO). For the purpose of this evaluation, the bolt path was identified by the presence of a visible channel left in the skull or brain or by identification of bone fragments pushed into the brain by the bolt. The depth of penetration was determined based on the location of the deepest bone fragment.

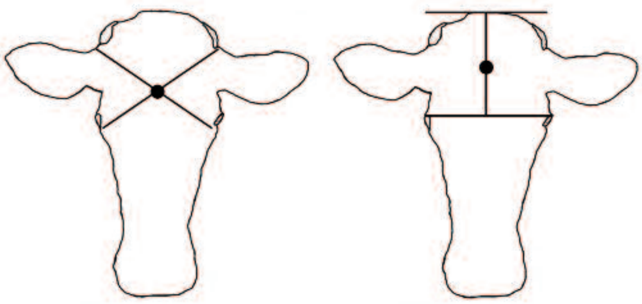
Unique cases

In an effort to further clarify the impact of variations in head size and shape, three heads from the Adult group with unique age and breed characteristics received additional evaluation. They were from each of the following: a six-year old Brahman cow, a ten-year old horned Hereford bull and a mature crossbred bucking bull. Limited availability of heads with these characteristics prevented comparison of the two shot placements between heads with the same or similar characteristics. Following acquisition of the initial CT scan, in an effort to examine the differences between the two shot locations in heads of these unique types, two of the heads were shot again in the alternate shot position. In the third head, a needle was placed at the alternate shot location (PCB was not readily available at the time of CT for this head). Computed tomography was then repeated to allow direct comparison of the two shot locations within the same heads. These secondary CT images were not evaluated by the radiologists and were not included in any statistical analyses.

Table 1 Specifications of each penetrating bolt utilised in this study and the kinetic energy of each bolt and power load combination.

	Bolt	
	Medium	Long
Overall length (mm)	187.9	206.5
Stem length (mm)	155.8	174.4
Stem diameter (mm)	11.9	11.9
Weight (kg)	0.22	0.23
Kinetic energy (J)		
Yellow	241	
Blue	295	
Orange		338

Figure 1

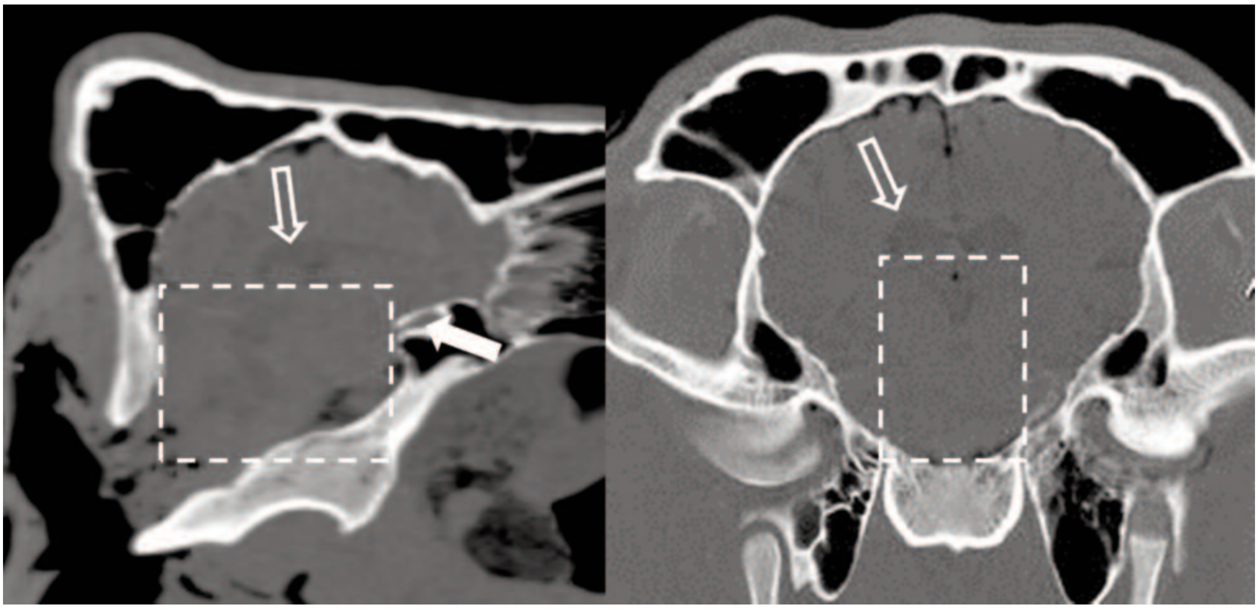


LOW shot position (left) denoted as the intersection of two lines drawn from the medial canthus of each eye to the opposite horn or top of the opposite ear. HIGH shot position (right) denoted as a point on midline halfway between the top of the poll and a line drawn between the lateral canthus of each eye.

Statistical analysis

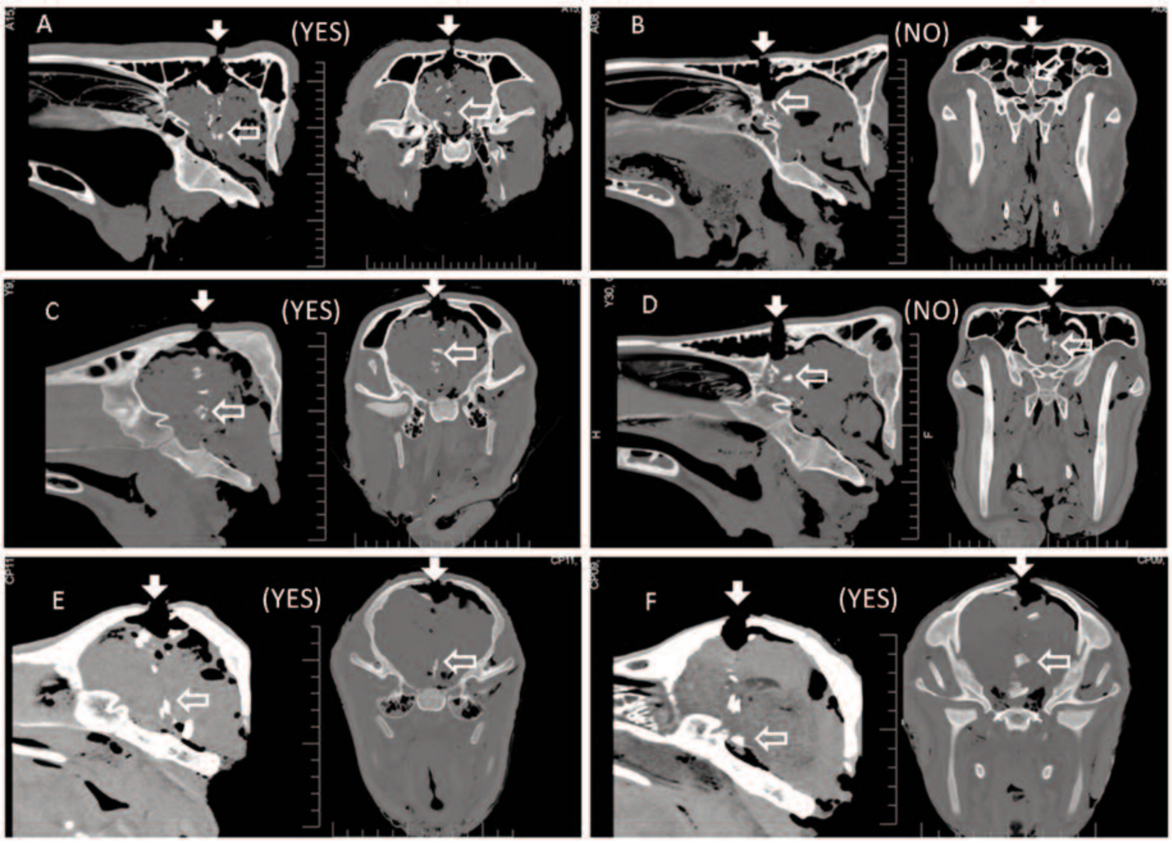
Data were compared between shot locations within each age group via the Fisher's Exact Test (GraphPad Quick Calcs online calculator, accessed at: http://graphpad.com/quickcalcs/contingency1.cfm). The level of significance was set at $P \leq 0.05$.

Figure 2



Computed tomography images of an intact bovine brain depicting the landmarks for determining if brainstem disruption occurred following penetrating captive-bolt shot. The brainstem was considered to lie caudal to the presphenoid bone (solid block arrow), deep to the third ventricle (open block arrow) and within 1.5 cm of the midline. The brainstem was considered to lie within the area of the dashed rectangles.

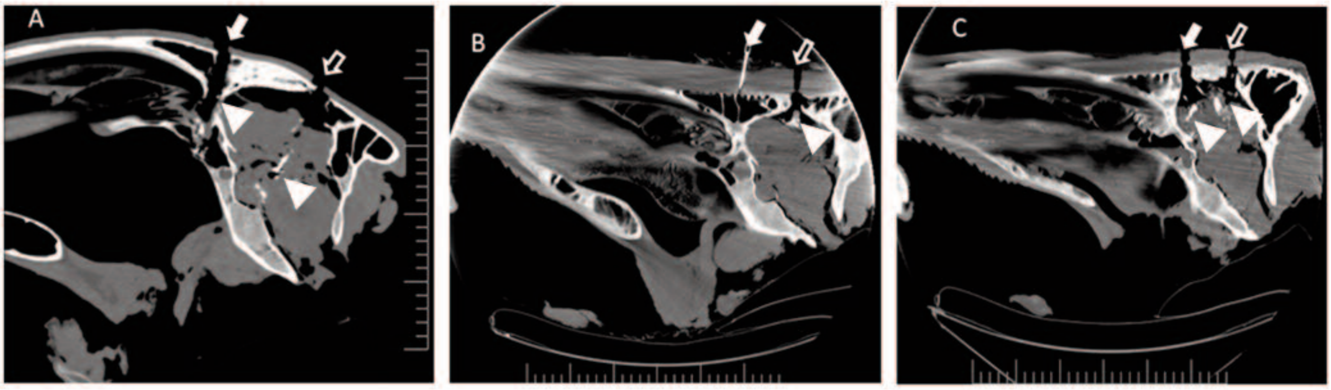
Figure 3



Representative sagittal and transverse CT images showing the site of bolt penetration (solid arrows) and the bolt path indicated by bone fragments (open arrows) for each age and shot placement combination. Score for brainstem disruption is indicated by (YES) or (NO) for each image. (A) Adult, HIGH position, (B) Adult, LOW position, (C) Young, HIGH position, (D) Young, LOW position, (E) Neonate, HIGH position, (F) Neonate, LOW position.

https://doi.org/10.7120/09627286.25.3.347 Published online by Cambridge University Press

Figure 4



Sagittal CT images of heads with unique breed types showing both HIGH (open arrows) and LOW (solid arrows) shot positions within the same head. Note the bolt paths indicated by arrowheads. (A) Six-year old Brahman cow, (B) ten-year old horned Hereford bull, note LOW position indicated by needle placed in skin, needle was used because captive bolt was not readily available at the time of the CT scan and (C) mature crossbred bucking bull.

Results

Shot positions were 18 HIGH, 14 LOW in Adult, 16 HIGH, 19 LOW in Young, and 11 HIGH, 14 LOW in Neonatal cattle heads. Brainstem disruption occurred in 16/18 adult HIGH and 7/14 adult LOW heads ($P = 0.0225$), 13/16 young HIGH and 11/19 young LOW heads ($P = 0.1667$), and 11/11 neonate HIGH and 14/14 neonate LOW heads ($P = 1.0$). Representative CT images from each age and shot placement group are shown (Figure 3).

Notable differences between shot placement locations were observed in individual heads with unique breed characteristics (Figure 4).

Discussion

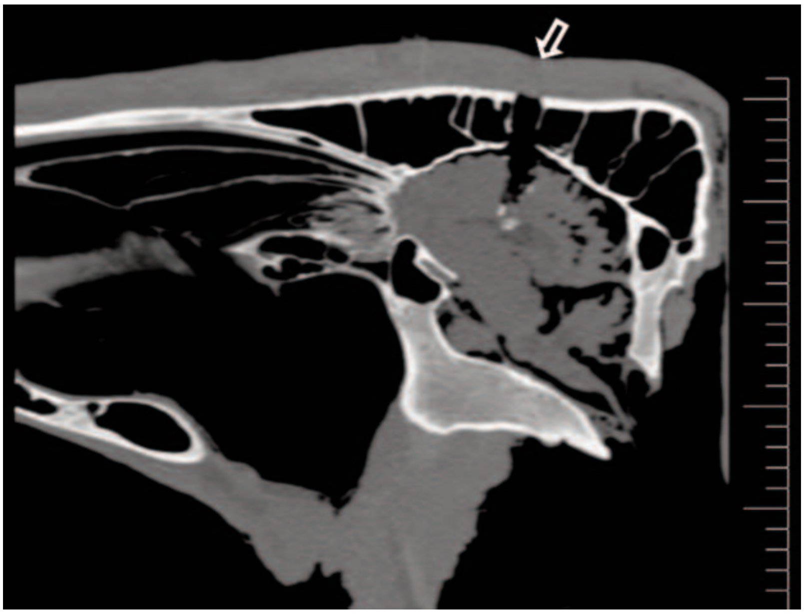
Few published studies have investigated shot placement specifically with a view on PCB as a single-step euthanasia method. Current publications describing PCB euthanasia recommend application of a secondary step following PCB shot to ensure death (AABP 2013; AVMA 2013). In contrast, multiple studies have described the importance of shot placement for achieving an adequate stun prior to exsanguination during slaughter. Atkinson *et al* (2013) investigated stun quality at a commercial slaughter facility. In that study, an accurate shot was defined as being within 2 cm of the intersection of two lines drawn from the eye to the base of the opposite horn or upper edge of the opposite ear. Shots outside of this area were considered to be inaccurate. Adequate stunning occurred in 89.6% of cattle shot accurately while only 65% of inaccurately shot cattle were adequately stunned. In a survey of over 1,400 cattle slaughtered in commercial slaughter plants, Von Wenzlawowicz *et al* (2012) reported that 8% of cattle received an inaccurate shot and that 9.2% of cattle were inadequately stunned. Grandin (2002) reported inaccurate shot placement as a cause of return to sensibility problems in a large survey of beef slaughter plants.

The goal of the study reported here was to investigate the likelihood of direct physical disruption of the brainstem following a single PCB shot. The results of this study demonstrate that placing a PCB shot at a point midway between the top of the poll and a line drawn between the lateral canthus of each eye increases the probability of physically disrupting the brainstem via direct penetration of the bolt and/or bone fragments.

In cattle over 24 months of age shot in the HIGH location, failure to disrupt the brainstem occurred in 2/18 heads. One of these heads was from a mature Angus bull and the other was from a mature horned Hereford bull. In these heads, the bolt path was positioned directly over the brainstem and the reason for failure was inadequate depth of penetration such that the bolt failed to reach beyond the level of the third ventricle (Figure 5). Inadequate penetration may have been due to the large size of these heads and thickness of the skulls. Both heads had over 2 cm of soft tissue covering the frontal bone at the point of entry of the captive bolt.

Alternatively, the apparent lack of adequate penetration may have been due to a limitation of the method used to assess bolt-path depth. Freezing and thawing the heads softened the brains such that the tissue collapsed back into the bolt path prior to the CT scan, making it impossible to determine the bolt path by observing a channel left in the soft tissue. The bolt path could only be determined by visualising bone fragments that were pushed into the brain by the bolt. It is possible that the bolt may have penetrated beyond the position of the deepest bone fragment. However, given that the only cases of apparently inadequate penetration occurred in large heads from mature bulls, it is likely that penetration was limited to some degree by the thickness of the skull and soft tissues covering the frontal bone. A more powerful power load (black) which might have improved penetration is available for use in this PCB equipment but these charges were not used in this study. Several authors (Grandin 2002; Gregory *et al* 2007; Gouveia *et al* 2009; Atkinson *et al* 2013) have reported that bulls are more difficult to stun effectively compared to other classes of cattle. For comparison, for heads in shot in the LOW position, failure to disrupt the brainstem occurred in 7/14

Figure 5



Sagittal CT image from a ten-year old Angus bull. The bolt path (open arrow) failed to reach deep to the third ventricle. Note that bone fragments are contained within the third ventricle but failed to pass deep to the third ventricle.

heads. In all of these heads, the bolt path was too far rostral to directly impact the brainstem. This group included heads from two mature Angus bulls. In one of those heads, the bolt entered the extreme rostral aspect of the calvarium, nearly missing the brain entirely. These results demonstrate the importance of the relative rostral-caudal placement in positioning the shot directly over the brainstem.

In cattle between 6 and 24 months of age shot in the HIGH position, failure to disrupt the brainstem occurred in 3/19 heads. All three of these animals were near the upper limits of age to be included in this group and their size approximated that of young adult animals. One of the animals had sizeable horns. In all three, failure occurred due to inadequate penetration depth. The CT images of these animals were similar to that shown in Figure 5. These results indicate the importance of selecting a longer bolt and/or increased power load for animals that approximate adult size. For comparison, failure to disrupt the brainstem occurred in 8/19 heads shot in the LOW position. In these eight heads, the bolt path was too far rostral to directly disrupt the brainstem.

Based on the model used in this study, brainstem disruption occurred in all neonatal heads, regardless of shot position. This finding is likely due to the small size of these heads which reduces the magnitude of the distance between the two shot locations. It is interesting to note that in the heads shot in the LOW position, the bolt path was only slightly caudal to the presphenoid bone and, in many cases, only a single bone fragment passed far enough caudal to enter the brainstem. In contrast, in the heads shot in the HIGH position, the bolt entered directly into the brainstem with considerable margin for error (See Figure 3 E and F).

The findings from heads with unique breed characteristics are interesting and shed particular light on the need for shot-placement landmarks that will compensate for cattle with different shaped heads. As the forehead of a bovine becomes longer, the distance between the centre of the brain and the position of the eyes appears to become greater. This is evidenced by the findings in different ages and types of cattle in this study. Although it appears that shooting neonatal animals at the HIGH shot location may offer a slightly greater margin for error, there is only a slight distance between the HIGH and LOW shot positions in these animals. Based on evidence from this study, the distance between the two shot locations in cattle with longer heads such as Brahman cattle or cattle with large horns, may be up to several centimeters. The landmarks used to define the HIGH shot position in this study appear to account for this variability in head shape and result in the shot being placed over the centre of the brain in a variety of cattle types.

It is important to note a number of limitations of the model used in this study. This study was performed on cadaver heads so inferences regarding the level of unconsciousness produced by a given shot cannot be made. Several factors influence the development and permanence of unconsciousness that occurs as a result of a PCB shot. In addition to direct brain tissue destruction caused by the bolt, other factors such as acceleration/deceleration of the brain, sheer forces caused by movement of the brain within the skull, and changes in intracranial pressure caused by brain haemorrhage can have profound effects on consciousness alone or in combination with one another. In a review of traumatic brain injury, Finnie and Blumbergs (2002) described the effects of each of these factors on brain function and consciousness. In the present study, traumatic brain injury could not be meaningfully assessed due to the freezing and thawing of the heads (Gilliam *et al* 2012).

The authors used direct physical penetration of the brainstem as the outcome measure in this study because traumatic brain injury scoring and evaluation of other factors, such as intracranial haemorrhage were not possible when using

https://doi.org/10.7120/09627286.25.3.347 Published online by Cambridge University Press

frozen/thawed cadaver heads. Although direct penetration of the brainstem may not be necessary to induce unconsciousness (Lambooy 1982; Finnie 1995), immediate and permanent unconsciousness followed by death should occur when direct physical penetration of the brainstem is achieved.

Conclusion

Based on the findings of this study, physical disruption of the brainstem can be more readily achieved when a PCB is placed on the midline at a point halfway between the poll and a line drawn between the lateral canthus of each eye. These shot-position landmarks appear to provide a single set of landmarks that will provide maximal opportunity to physically disrupt the brainstem. Compared to the more traditional LOW shot position, the HIGH shot position significantly improved effectiveness in terms of brainstem disruption in adult cattle. Careful consideration should be given to selecting a bolt with appropriate length combined with the appropriate power load to achieve penetration to a depth adequate to reach the brainstem. When in doubt, the authors recommend using the longest bolt and strongest power load available. It is important to note that in animals with very large heads, direct penetration of the brainstem may not be achievable due to limited penetration depth even with a specialised captive-bolt device.

The shot-placement landmarks described in this study should account for the significant variations in head shape that occur in cattle resulting in placement of the captive bolt directly over the brainstem increasing the opportunity to cause direct physical disruption of the brainstem.

Acknowledgements

The authors thank Charles Bildstein and Bunzl Processor Division for providing equipment and Carolyn Rodebush and Leslie Shearer for technical assistance. Funding was provided by a joint grant from the United States Department of Agriculture and the United States Department of Homeland Security.

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