Title: Foundational investigations of tissue dimensions and their relation to captive bolt application sites on cadaver heads from mature swine – **NPB #19-227**

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Industry Summary:

Three penetrating captive bolt application sites were tested on cadaver heads from sows (n = 111) and boars (n = 46) with estimated BW > 200 kg. Objective 1 of this study was to determine the soft, cranial, and total tissue depths, cross-sectional brain area, and bolt-brain contact for each captive bolt site. Objective 2 was to determine if relationships exist between the measurements outlined in Objective 1 and external head dimensions, including snout to poll distance, distance between the eyes, and maximum deflection distance between a straight line from snout to poll and surface of the front of the head. The penetrating captive bolt device used in this study was a Jarvis Model PAS – Type P 0.25R equipped with Long Stunning Rod Nosepiece Assembly and 3.5 grain powder cartridges. The three treatments were: FRONTAL – shot placed 3.5 cm superior to a line drawn across the top of the eyes at midline, TEMPORAL – shot placed at the depression posterior to the lateral canthus of the eye within the plane between the lateral canthus and the base of the ear, or BEHIND EAR – shot placed directly caudal to the pinna of the ear on

the same plane as the eyes and targeting the middle of the opposite eye. Heads were obtained from a regional slaughter establishment after they were electrically stunned and slaughtered. On the same day, heads were transported to the University of Wisconsin – River Falls Meat Laboratory and stored in a walk-in cooler for approximately 62 h at 2-4° C prior to captive bolt shot application. On sampling days, each head was randomly assigned to one of the three captive bolt treatments and shot in a custom-fabricated benchtop-mounted brace that consisted of stainless steel bent to form a corner that the head could be firmly pushed against during the captive bolt shot. After the shot, each head was cut along the anticipated path of bolt travel on a meat bandsaw. After cutting, the two exposed internal surfaces of each head were digitally imaged with a reference ruler included in the image for later analysis of tissue thicknesses and exposed cross-sectional brain area with irregular area calculation software. The internal temperature of each head was collected with a thermographic camera during the same imaging session. After image collection, heads were disposed by rendering.

Bran damage was detected in digital images from 96.26% of sows and boars combined in the FRONTAL treatment, 47.27% in the TEMPORAL treatment, and 27.78% in the BEHIND EAR treatment. Soft tissue thickness was greatest for BEHIND EAR (59.2 ± 1.4 mm), followed by TEMPORAL (51.7 ± 1.4 mm), and was least for the FRONTAL treatment (6.0 ± 0.05 mm). Cranial thickness was greatest for FRONTAL heads (41.0 ± 1.5 mm), followed by BEHIND EAR heads (30.9 ± mm), and was least for TEMPORAL heads (19.8 ± 1.5 mm). Total tissue thickness was greatest in BEHIND EAR heads (90.1 ± 1.3 mm), followed by TEMPORAL heads (71.5 ± 1.3 mm), and was least for FRONTAL heads (47.0 ± 1.3 mm). Cross-sectional brain area was greatest ($P < 0.0001$) for FRONTAL heads (4194.4 ± 160.3 mm^2), followed by BEHIND EAR heads (2618.7 ± 160.3 mm^2), and least for TEMPORAL heads (1546.2 ± 160.3 mm^2). As maximum deflection distance between a straight line from snout to poll and surface of the front of the head increased, cranial thickness and total tissue thickness in the FRONTAL position increased. Cranial thickness and total tissue thickness also increased as pig weight increased.

It is important to emphasize that the findings of this study are specific to the captive bolt pistol that was used. Multiple models are commercially available, each with its own operating and performance parameters. Our findings suggest that the FRONTAL application site presents the least risk for failure of captive bolt euthanasia because the total tissue thickness in the FRONTAL position is less than the TEMPORAL and BEHIND EAR positions and the cross-sectional brain area is larger in the FRONTAL position compared to the TEMPORAL and BEHIND EAR positions. Although the FRONTAL position displayed the least total tissue thickness, it is very important to note that the actual thickness was approximately 4.7 cm, which is a substantial distance for a captive bolt to reach and may have been near the maximum bolt travel distance for the captive bolt gun used in our study. In addition, as the front of the head developed a more dish-shaped appearance, as indicated by the maximum deflection distance, total tissue thickness increased in the FRONTAL position, suggesting that bolt penetration depth should be a very important consideration when selecting a penetrating captive bolt gun for the euthanasia of sows and boars > 200 kg BW.

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Key Findings:

- The total tissue thicknesses in all three locations (frontal, temporal, and behind the ear) were substantial. The least tissue thickness was approximately 4.7 cm in the frontal location.
- The pistol-type captive bolt gun with long bolt nosepiece assembly that was used in this study did not appear to have sufficient bolt reach to contact the brain in the temporal and behind the ear locations.
- As the front of the head became more dish-shaped in sows > 200 kg body weight, the total tissue thickness in the frontal location increased.
- The total tissue thickness was least and cross-sectional brain area was greatest in the frontal position, suggesting a greater likelihood of successful captive bolt euthanasia in that location compared to temporal and behind the ear.

Keywords: captive bolt, euthanasia, stunning, swine

Scientific Abstract:

Three penetrating captive bolt (PCB) application sites were tested on cadaver heads from sows and boars with estimated BW > 200 kg. The objectives were to determine the tissue depth, cross-sectional brain area (CSBA), regions of brain damage, and visible brain damage (BD) for each of the sites; and to determine the relationship between external dimensional head measurements and tissue depth, CSBA, regions of brain damage, and BD associated with each of the sites. The PCB device was a Jarvis Model PAS – Type P 0.25R equipped with Long Stunning Rod Nosepiece Assembly and 3.5 grain powder cartridges. The three treatments were: FRONTAL – shot placed 3.5 cm superior to a line drawn across the top of the eyes at midline, TEMPORAL –

shot placed at the depression posterior to the lateral canthus of the eye within the plane between the lateral canthus and the base of the ear, or BEHIND EAR – shot placed directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye. Heads were obtained from 111 sows and 46 boars that were slaughtered at a regional abattoir and stored in a walk-in cooler for approximately 62 h at 2-4° C prior to treatment. BD was detected in digital images from 96.26% (95% CI: 87.43 – 99.95%) of sows and boars combined in the FRONTAL treatment, 47.27% (95% CI: 33.65 – 61.20%) in the TEMPORAL treatment, and 27.78% (95% CI: 16.46 – 41.64%) in the BEHIND EAR treatment. Soft tissue thickness was greatest ($P < 0.0001$) for BEHIND EAR (59.2 ± 1.4 mm), followed by TEMPORAL (51.7 ± 1.4 mm), and was least for FRONTAL (6.0 ± 0.05 mm). Cranial thickness was greatest ($P < 0.0001$) for FRONTAL (41.0 ± 1.5 mm), followed by BEHIND EAR (30.9 ± mm), and was least for TEMPORAL (19.8 ± 1.5 mm). Total tissue thickness was greatest ($P < 0.0001$) in BEHIND EAR (90.1 ± 1.3 mm), followed by TEMPORAL (71.5 ± 1.3 mm), and was least for FRONTAL (47.0 ± 1.3 mm). CSBA was greatest ($P < 0.0001$) for FRONTAL (4194.4 ± 160.3 mm^2), followed by BEHIND EAR (2618.7 ± 160.3 mm^2), and least for TEMPORAL (1546.2 ± 160.3 mm^2). Positive linear relationships were identified regarding the impacts of maximum deflection distance of the frontal profile of the head and head weight on cranial thickness and total tissue thickness in the FRONTAL position in a subset of 19 sow heads ($P < 0.0001$). FRONTAL placement of the PCB used in this study may present the least risk of euthanasia failure in sows and boars > 200 kg BW.

Introduction:

Penetrating captive bolt (PCB) is a method of euthanasia approved for use in swine, specifically sows, boars, and grower-finishers by the American Veterinary Medical Association

(AVMA, 2013; AVMA, 2020) and jointly approved by the National Pork Board and American Association of Swine Veterinarians (NPB and AASV, 2016). Although the method is approved, and commonly used in industry, it has not been scientifically validated as effective for sows and boars estimated to be over 200 kg (Woods, 2012). Specifically, Woods (2012) found that that the common frontal application was not 100% effective in sows and boars that were visually estimated to be over 200 kg in both trials with anesthetized animals and field trials on production sites. The common PCB placement for pigs is a frontal location (AVMA, 2013; AVMA, 2020; NPB and AASV, 2016); however, two alternative sites have been identified: temporal and behind the ear toward the opposite eye (AVMA, 2013). At the time of this study, the only published data to validate the behind the ear placement was focused on market weight pigs (Anderson et al., 2019). Validation studies for the temporal placement did not exist in the published literature at the time of this study. This study was designed to serve as the first step in scientifically validating the behind the ear and temporal placement for sows and boars larger than 200 kg BW.

The amount of pain and suffering experienced by an animal at the time of death is highly variable and dependent on the selected euthanasia method (AVMA, 2020; OIE, 2016). Thus, it is important to consider how an animal dies and the amount of pain and suffering when selecting a euthanasia method. The objectives of this study were (a) to determine the tissue depth, cross-sectional brain area, regions of brain damage, and bolt-brain contact associated with the frontal, temporal, and behind the ear shot placements for the euthanasia of swine via PCB on sow and boar heads, and (b) to determine the relationship between external dimensional head measurements and tissue depth, cross-sectional brain area, regions of brain damage, and bolt-brain contact associated with the frontal, temporal, and behind the ear shot placements.

Following the initiation of this study, we realized that bolt-brain contact could not be reliably discerned from brain damage associated with bone fragment movement during passage of the bolt. As a result, we assessed the occurrence of visible brain damage and refer to brain damage instead of bolt-brain contact in this report. Our hypothesis was that differences in soft tissue thickness, cranial thickness, total tissue thickness, cross-sectional brain area, overall brain damage, and regions of brain damage would be detected between PCB application site treatments.

Objectives:

The objectives of this study were:

(a) to determine the tissue depth, cross-sectional brain area, regions of brain damage, and bolt-brain contact associated with the frontal, temporal, and behind the ear shot placements for the euthanasia of swine via PCB on sow and boar heads,

(b) to determine the relationship between external dimensional head measurements and tissue depth, cross-sectional brain area, regions of brain damage, and bolt-brain contact associated with the frontal, temporal, and behind the ear shot placements.

For both objectives, visible brain damage was assessed in place of bolt-brain contact following the discovery of brain damage, probably due to bone fragment movement, in regions that were likely not reached by the bolt.

Materials and Methods:

Animal use protocol

It was not necessary to submit an animal use protocol to the University of Wisconsin – River Falls Institutional Animal Care and Use Committee (IACUC) because live animals were not directly manipulated in this study. The pigs from which the heads were obtained were slaughtered at a commercial slaughter establishment under inspection by the United States Department of Agriculture Food Safety and Inspection Services (USDA FSIS) in accordance with regulations in 9 CFR 313. The heads used in this study were acquired as products that were not suitable for human consumption. The exemption from IACUC approval followed the precedent established by Anderson et al. (2019, 2021).

Description of cadaver heads

Cadaver heads were obtained from 111 sows (average BW = 231.76 kg) and 46 boars (average BW = 229.87 kg) that were commercially slaughtered at a regional processing facility under federal inspection. Estimated live weight was determined for each source sow or boar retrospectively, using average dressing percentage from the processing facility (58%) and the hot carcass weight of skinned carcasses. Additionally, 4.545 kg was added to the weight of each source pig to account for the neck tissue that was left on the heads (formula: hot carcass weight/0.58 + 4.535 kg). All heads had skin on and intact jowls, with approximately 6 cm of neck tissue left behind the ear to prevent soft tissue distortion at the PCB application site. All heads were packaged in large storage totes (Sterilite 1466 – 27 Gallon Industrial Tote, Sterilite Corp., Townsend, MA) with 2 heads per tote, prior to unrefrigerated transport (distance travelled: 188 km) to the University of Wisconsin – River Falls Meat Science Laboratory. Heads were stored in the storage totes with the lid slightly offset inside a walk-in cooler for approximately 62 h at 2-4° C prior to PCB application. The mean temperature of the exposed internal cranial surface after post-application head processing was 7.70 ± 1.83° C.

Description of captive bolt tool and placement

The penetrating captive bolt (PCB) device used in this study was a Jarvis Model PAS – Type P 0.25R Caliber Captive Bolt Pistol (Order #: 4144035, Jarvis Corp., Middletown, CT) equipped with Long Stunning Rod Nosepiece Assembly (Order #: 3116605, Jarvis Corp.). Jarvis Orange Powder Cartridges 0.25R Caliber, 3.5 GR (Order #: 1176019, Jarvis Corp.) were used for all PCB applications in this study. Orange cartridges were selected for use based on manufacturer recommendations that not more than 5% of pistol PAS type PCB applications may occur with Black cartridges (4.0 GR) without likely damage to the PCB and additional danger to the operator and bystanders. The Orange cartridge is the highest power cartridge that is approved by the manufacturer for use in the pistol PAS type PCB. Three PCB placement treatments (Figure 1) were applied in this study: FRONTAL – shot placed 3.5 cm superior to a line drawn across the top of the eyes at midline (Woods et al., 2010), TEMPORAL – shot placed at the depression posterior to the lateral canthus of the eye within the plane between the lateral canthus and the base of the ear, or BEHIND EAR – shot placed directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye (Anderson et al., 2019; AVMA, 2013). For all PCB applications, each head was placed in a custom-fabricated benchtop-mounted brace of stainless steel bent to form a corner so that each head could be pushed into the corner and be firmly secured for each of the three treatments (Figure 1).

On sampling days, bolt speed was tested at the beginning and end of sampling. The PCB was tested before use at the beginning of sampling and prior to cleaning at the end of sampling. The average bolt speed for all sampling days was 48.42 ± 2.11 m/s.

Post-application head processing

Following the application of the shot location treatment, each head was cut along the bolt path with a meat band saw. Following each cut, digital images were collected from both sides of each intracranial surface. Thermal images (Model E8, FLIR Systems, Boston, MA) were also collected from both sides of each exposed intracranial surface for temperature assessment. Thermal images were collected both with and without the brain for each head. Brain temperature was determined using thermal images collected with the brain. Digital images were collected both with and without the brain for each head. A painted wooden dowel was included in a duplicate set of images to indicate bolt path. All images were collected with the thermal camera and digital camera positioned 50.8 cm directly above and perpendicular to the exposed cut surface.

Tissue and Cranial Measurements

Measurements of soft tissue thickness (mm), cranial thickness (mm), and cross-sectional brain area (mm^2) were determined from images collected at the time of head processing following procedures adapted from Anderson et al., 2021. All images included a 15.0 cm ruler that was used as reference for an online irregular area calculator (SketchandCalc, ICalc, Inc., Palm Coast, FL). Soft tissue thickness referred to the tissue from the application site to the exterior surface of the cranium. This measurement was reported on both sides of the exposed bolt path. Cranial thickness referred to the thickness from the exterior surface of the cranium to the interior surface of the cranium along the bolt path. This measurement was reported on both sides of the exposed bolt path. Total tissue thickness (mm), which referred to the total soft tissue and cranial thickness from the site of application to the interior surface of the cranium, was determined from the summation of the soft tissue and cranial thickness for each cadaver head. This measurement was reported on both sides of the exposed bolt path. Soft tissue thickness, cranial thickness, and total tissue thickness were determined by averaging the measurements from the two halves of each head on both sides of the exposed bolt path. Cross-sectional brain area (mm^2) referred to the cross-sectional surface area of the exposed brain within the plane of bolt travel as described by Anderson et al. (2019). Measurements of cross-sectional brain area were calculated from both halves of each head along the paths of bolt travel and averaged prior to statistical analysis.

Brain Damage Assessment

Brain damage and regions of brain damage were determined using digital images of the brain that were collected at the time of head processing. Damage to regions of the brain was assessed on a yes/no basis where yes meant there was visually detectable damage to the brain and no meant there was no visually detectable damage to the brain: frontal lobe, parietal lobe, temporal lobe, occipital lobe, corpus callosum, diencephalon, mesencephalon, brainstem, and cerebellum (adapted from Wagner et al., 2019). Heads were considered to have brain damage if one or more regions of the brain had visually detectable damage. It was not possible to reliably discern between actual bolt contact with the brain and bone fragment damage, but it was possible to assess and reliably report brain damage.

Brain maps that depicted regions of the brain were developed for each PCB placement (FRONTAL, TEMPORAL, and BEHIND EAR) to guide the assessment of brain damage. These brain maps were adapted from images of rostrocaudal slices of the porcine brain (Wouterlood and van de Berg, 2010). For the FRONTAL treatment, the following regions and structures were included on the brain map and assessed for damage: parietal lobe, frontal lobe, occipital lobe, corpus callosum, mesencephalon, diencephalon, brainstem, and cerebellum. For the TEMPORAL treatment, the following regions and structures were included on the brain map and assessed for damage: parietal lobe, occipital lobe, corpus callosum, and diencephalon. For the

BEHIND EAR treatment, the following regions and structures were included on the brain amp and assessed for damage: parietal lobe, temporal lobe, occipital lobe, corpus callosum, diencephalon, mesencephalon. Brain regions or structures that were not included in the brain map for each treatment were categorized as 'no damage'.

External head measurements

On a subset of 56 sows from two sampling days, the following external head measurements were collected: snout to poll distance (cm), distance between optic orbits (cm), and maximum deflection distance (cm). Snout to poll distance referred to the distance from the tip of the snout to the first point of contact between a taught measurement tape and the poll. Distance between optic orbits referred to the distance between the medial aspects of the optic orbits. Maximum deflection distance referred to the maximum distance from a straight edge that was placed between the tip of the snout and the poll or the first point where the straight edge touched the head when placed from the tip of the snout. All measurements except were collected in duplicate by two trained data collection technicians using a flexible measuring tape (Singer 218 60 in, The Singer Company Ltd., Boston, MA), or a rigid ruler for maximum deflection distance, and were averaged prior to statistical analysis. Head weight (kg) was collected for all heads in the study using a benchtop scale which was calibrated prior to use on each sampling day.

Statistical analyses

All continuous data for PCB placement treatment (FRONTAL, BEHIND EAR, TEMPORAL) effects were analyzed using models constructed within the MIXED procedure of SAS 9.4 (Statistical Analysis System Institute, Inc., Cary, NC). Models included fixed effects of sex (SOW, BOAR), treatment (FRONTAL, BEHIND EAR, TEMPORAL) and the interaction of sex and treatment. Mean separation was determined by using Student's T-tests, protected by the Tukey-Kramer adjustment. Differences between means were identified when $\alpha \leq 0.05$.

Data with binomial outcomes were analyzed with a generalized linear mixed model in the GLIMMIX procedure of SAS 9.4 (Statistical Analysis System Institute, Inc., Cary, NC) with a logit link specified for binomial data. The model included fixed effects of sex (SOW, BOAR), treatment (FRONTAL, BEHIND EAR, TEMPORAL) and the interaction of sex and treatment. Pair-wise comparisons were adjusted for multiple comparisons using Tukey methods. Treatment effects on specific regions of brain damage resulted in multiple instances where treatment and outcome (presence or absence of brain damage) combinations were not observed because the bolt entry point and plane of travel was different between treatments and resulted in instances where specific brain regions were not accessible to the bolt path. Since statistical models would not converge as a result of this difference, 95% confidence intervals for the occurrence of brain damage were calculated in Microsoft Excel 2010 (Microsoft Corp., Spokane, WA) using the Fisher's Exact method.

The relationship between external head measurements (snout to poll distance, distance between ocular orbits, maximum deflection distance of the frontal aspect of the head from a straight line from snout to poll, and head weight were assessed for correlations with soft tissue thickness, cranial thickness, and total tissue thickness of a subset of 19 heads in the FRONTAL treatment using the Regression procedure in SAS 9.4 (Statistical Analysis System Institute, Inc., Cary, NC).

Results:

Tissue measurements and cross-sectional brain areas collected in this study for all sows and boars combined, sows only, and boars only can be observed in Table 1. For all sows and boars combined, soft tissue thickness, cranial thickness, total tissue thickness, and cross-sectional brain area were significantly different ($P < 0.05$) between the FRONTAL, TEMPORAL, and BEHIND EAR penetrating captive bolt (PCB) placement treatments. Soft tissue thickness was greatest ($P < 0.0001$) for BEHIND EAR heads (59.2 ± 1.4 mm), followed by TEMPORAL heads (51.7 ± 1.4 mm), and was least for FRONTAL heads (6.0 ± 0.05 mm). Cranial thickness was greatest ($P < 0.0001$) for FRONTAL heads (41.0 ± 1.5 mm), followed by BEHIND EAR heads (30.9 ± mm), and was least for TEMPORAL heads (19.8 ± 1.5 mm). Total tissue thickness was greatest ($P < 0.0001$) in BEHIND EAR heads (90.1 ± 1.3 mm), followed by TEMPORAL heads (71.5 ± 1.3 mm), and was least for FRONTAL heads (47.0 ± 1.3 mm). Cross-sectional brain area was greatest ($P < 0.0001$) for FRONTAL heads (4194.4 ± 160.3 mm^2), followed by BEHIND EAR heads (2618.7 ± 160.3 mm^2), and least for TEMPORAL heads (1546.2 ± 160.3 mm^2).

For sows only, soft tissue thickness, cranial thickness, total tissue thickness, and cross-sectional brain area were significantly different ($P < 0.05$) between the FRONTAL, TEMPORAL, and BEHIND EAR treatments. Soft tissue thickness was greatest ($P < 0.0001$) for BEHIND EAR heads (59.1 ± 1.5 mm), followed by TEMPORAL heads (52.2 ± 1.5 mm), and least for FRONTAL heads (5.6 ± 1.5 mm). Cranial thickness was greatest ($P < 0.0001$) for FRONTAL heads (47.1 ± 1.4 mm), followed by BEHIND EAR heads (30.2 ± 1.4 mm), and was least for TEMPORAL heads (17.6 ± 1.4 mm). Total tissue thickness was greatest ($P < 0.0001$) for BEHIND EAR heads (89.3 ± 1.3 mm), followed by TEMPORAL heads (69.8 ± 1.3 mm), and least for FRONTAL heads (52.7 ± 1.3 mm). Cross sectional brain area was greatest ($P < 0.0001$) for FRONTAL heads (4330.5 ± 199.8 mm^2), followed by BEHIND EAR heads (2769.8 ± 199.8 mm^2), and least for TEMPORAL heads (1876.5 ± 199.8 mm^2).

For boars only, soft tissue thickness, total tissue thickness, and cross-sectional brain area were significantly different ($P < 0.05$) between the FRONTAL, TEMPORAL, and BEHIND EAR treatments. Soft tissue thickness was greatest ($P < 0.0001$) for BEHIND EAR heads (59.3 ± 2.1 mm), followed by TEMPORAL heads (51.1 ± 2.1 mm), and least for FRONTAL heads (6.4 ± 2.1 mm). Cranial thickness for boars only was significantly different ($P < 0.05$) between only the FRONTAL (34.8 ± 3.2 mm) and TEMPORAL (22.1 ± 3.2 mm) treatments, but neither treatment differed from the BEHIND EAR (31.6 ± 3.2 mm) treatment ($P > 0.05$). Total tissue thickness greatest ($P < 0.0001$) for BEHIND EAR heads (90.9 ± 2.4 mm), followed by TEMPORAL heads (73.2 ± 2.4 mm), and least for FRONTAL heads (41.2 ± 2.4 mm). Cross sectional brain area was greatest ($P < 0.0001$) for FRONTAL heads (4058 ± 130.5 mm^2), followed by BEHIND EAR heads (2467.5 ± 130.5 mm^2), and least for TEMPORAL heads (1216.0 ± 130.5 mm^2).

Overall brain damage observations from this study for combined sows and boars, sows only, and boars only can be observed in Table 2. Brain damage was detected in 96.26% (95% CI: 87.43 – 99.95%) of all sows and boars combined with the FRONTAL treatment, 47.27% (95% CI: 33.65 – 61.20%) of all sows and boars combined with the TEMPORAL treatment, and 27.78% (95% CI: 16.46 – 41.64%) of all sows and boars combined with the BEHIND EAR treatment. Brain damage was detected in 96.67% (95% CI: 82.78 – 99.92%) of sows with the FRONTAL treatment, 56.76% (95% CI: 39.49 – 72.90%) of sows with the TEMPORAL treatment, and 15.00% (95% CI: 5.71 – 29.84%) of sows with the BEHIND EAR treatment.

Brain damage was detected in 100.00% (95% CI: 73.53 – 100.00%) of boars with the FRONTAL treatment, 27.78% (95% CI: 9.69 – 53.48%) of boars with the TEMPORAL treatment, and 64.29% (95% CI: 35.14 – 87.24%) of boars with the BEHIND EAR treatment.

Damage to specific regions and structures of the brain for all combined sows and boars can be observed in Table 3. Damage to the frontal lobe was detected in 54.67% (95% CI: 38.76 – 70.15%) heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 6.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 6.60%) of heads shot in the BEHIND EAR treatment. Damage to the parietal lobe was detected in 97.62% (95% CI: 87.43 – 99.94%) of heads shot in the FRONTAL treatment, 54.55% (95% CI: 40.55 – 68.03%) of heads shot in the TEMPORAL treatment, and 20.37% (95% CI: 10.63 – 33.53%) of heads shot in the BEHIND EAR treatment. Damage to the temporal lobe was detected in 0.00% (95% CI: 0.00 – 8.41%) of heads shot in the FRONTAL treatment, 18.18% (95% CI: 9.08 – 30.90%) of heads shot in the TEMPORAL treatment, and 12.96% (95% CI: 5.37 – 24.90%) of heads shot in the BEHIND EAR treatment. Damage to the occipital lobe was detected in 80.95% (95% CI: 65.88 – 91.40%) of heads shot in the FRONTAL treatment, 1.82% (95% CI: 0.05 – 9.72%) of heads shot in the TEMPORAL treatment, and 20.37% (95% CI: 10.63 – 33.53%) of heads shot in the BEHIND EAR treatment. Damage to the corpus callosum was detected in 88.10% (95% CI: 74.37 – 96.02%) of heads shot in the FRONTAL treatment, 10.91% (95% CI: 4.11 – 22.25%) of heads shot in the TEMPORAL treatment, and 9.26% (95% CI: 3.08 – 20.30%) of heads shot in the BEHIND EAR treatment. Damage to the diencephalon was detected in 42.86% (95% CI: 27.72 – 59.04%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 6.49%) of heads shot in the TEMPORAL treatment, and 1.85% (95% CI: 0.05 – 9.89%) of heads shot in the BEHIND EAR treatment. Damage to the mesencephalon was detected in 2.38% (95% CI:

0.06 – 12.57%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 6.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 6.60%) of heads shot in the BEHIND EAR treatment. Damage to the brainstem was detected in 2.38% (95% CI: 0.06 – 12.57%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 6.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 6.60%) of heads shot in the BEHIND EAR treatment. Damage to the cerebellum was detected in 4.76% (95% CI: 0.58 – 16.16%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 6.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 6.60%) of head shot in the BEHIND EAR treatment.

Damage to specific regions and structures of the brain for sows only can be observed in Table 4. Damage to the frontal lobe was detected in 50.00% (95% CI: 31.30 – 68.70%) heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 9.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 8.81%) of heads shot in the BEHIND EAR treatment. Damage to the parietal lobe was detected in 97.67% (95% CI: 82.78 – 99.92%) of heads shot in the FRONTAL treatment, 67.57% (95% CI: 50.21 – 81.99%) of heads shot in the TEMPORAL treatment, and 10.00% (95% CI: 2.79 – 23.66%) of heads shot in the BEHIND EAR treatment. Damage to the temporal lobe was detected in 0.00% (95% CI: 0.00 – 11.57%) of heads shot in the FRONTAL treatment, 24.42% (95% CI: 11.74 – 41.20%) of heads shot in the TEMPORAL treatment, and 7.50% (95% CI: 1.57 – 20.39%) of heads shot in the BEHIND EAR treatment. Damage to the occipital lobe was detected in 80.00% (95% CI: 61.43 – 92.29%) of heads shot in the FRONTAL treatment, 2.70% (95% CI: 0.07 – 14.16%) of heads shot in the TEMPORAL treatment, and 12.50% (95% CI: 4.19 – 26.80%) of heads shot in the BEHIND EAR treatment. Damage to the corpus callosum was detected in 83.33% (95% CI: 65.28 –

94.36%) of heads shot in the FRONTAL treatment, 13.51% (95% CI: 4.54 – 28.77%) of heads shot in the TEMPORAL treatment, and 5.00% (95% CI: 0.61 – 16.92%) of heads shot in the BEHIND EAR treatment. Damage to the diencephalon was detected in 43.33% (95% CI: 25.46 – 62.57%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 9.49%) of heads shot in the TEMPORAL treatment, and 2.50% (95% CI: 0.06 – 13.16%) of heads shot in the BEHIND EAR treatment. Damage to the mesencephalon was detected in 3.33% (95% CI: 0.08 – 17.22%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 9.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 8.81%) of heads shot in the BEHIND EAR treatment. Damage to the brainstem was detected in 0.00% (95% CI: 0.00 – 11.57%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 9.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 8.81%) of heads shot in the BEHIND EAR treatment. Damage to the cerebellum was detected in 3.33% (95% CI: 0.08 – 17.22%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 9.49%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 8.81%) of head shot in the BEHIND EAR treatment.

Damage to specific regions and structures of the brain for boars only can be observed in Table 5. Damage to the frontal lobe was detected in 66.67% (95% CI: 34.89 – 90.08%) heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 18.53%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 23.16%) of heads shot in the BEHIND EAR treatment. Damage to the parietal lobe was detected in 100.00% (95% CI: 73.54 – 100.00%) of heads shot in the FRONTAL treatment, 27.87% (95% CI: 9.69 – 53.48%) of heads shot in the TEMPORAL treatment, and 50.00% (95% CI: 23.04 – 76.96%) of heads shot in the BEHIND EAR treatment. Damage to the temporal lobe was detected in 0.00% (95% CI: 0.00 – 26.46%)

of heads shot in the FRONTAL treatment, 5.56% (95% CI: 0.14 – 27.29%) of heads shot in the TEMPORAL treatment, and 28.57% (95% CI: 8.39 – 58.10%) of heads shot in the BEHIND EAR treatment. Damage to the occipital lobe was detected in 83.33% (95% CI: 51.59 – 97.91%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 18.53%) of heads shot in the TEMPORAL treatment, and 42.86% (95% CI: 17.66 – 71.14%) of heads shot in the BEHIND EAR treatment. Damage to the corpus callosum was detected in 100.00% (95% CI: 73.54 – 100.00%) of heads shot in the FRONTAL treatment, 5.56% (95% CI: 0.14 – 27.29%) of heads shot in the TEMPORAL treatment, and 21.43% (95% CI: 4.66 – 50.80%) of heads shot in the BEHIND EAR treatment. Damage to the diencephalon was detected in 41.67% (95% CI: 15.17 – 72.33%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 18.53%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 23.16%) of heads shot in the BEHIND EAR treatment. Damage to the mesencephalon was detected in 0.00% (95% CI: 0.00 – 26.46%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 18.53%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 23.16%) of heads shot in the BEHIND EAR treatment. Damage to the brainstem was detected in 8.33% (95% CI: 0.21 – 38.48%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 18.53%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 23.16%) of heads shot in the BEHIND EAR treatment. Damage to the cerebellum was detected in 8.33% (95% CI: 0.21 – 38.48%) of heads shot in the FRONTAL treatment, 0.00% (95% CI: 0.00 – 18.53%) of heads shot in the TEMPORAL treatment, and 0.00% (95% CI: 0.00 – 23.16%) of head shot in the BEHIND EAR treatment.

Linear relationships were identified for maximum deflection distance with frontal cranial thickness (Figure 2) and total frontal tissue thickness (Figure 3). Linear relationships were also identified for head weight with frontal cranial thickness (Figure 4) and total frontal tissue thickness (Figure 5). For both cranial and total tissue thickness, the estimate of thickness increased as deflection distance increased ($P < 0.0001$). Both values also increased as head weight increased ($P < 0.0001$). Woods (2012) investigated the impact of the frontal plate of the head with a description of "plank" vs. "dish" profiles. Our results support the concept that the frontal profile of the head and the underlying tissue thickness may be related.

Discussion

In an evaluation of the efficacy of a pistol type captive bolt kit that included penetrating and nonpenetrating assemblies for varying species and animal sizes in the frontal location for the euthanasia of swine, Woods (2012) concluded that penetrating captive bolt (PCB) was not consistently reliable or effective as a single-step euthanasia method for swine estimated to be larger than 200 kg; however, the method is effective as a single-step method of euthanasia for pigs weighing 2-120 kg. The European Food Safety Authority (EFSA) reported that PCB may not effectively cause a loss of consciousness in mature sows and boars and identified a need for the development and evaluation of a PCB device capable of effectively stunning, and ultimately killing, mature sows and boars (EFSA, 2004). Chevillion et al. (2004) reported that captive bolt is the recommended method of euthanasia for piglets over 8 kg, growing pigs, and breeding animals as a result of the efficacy, feasibility, and costs compared to other methods. Likewise, PCB is listed as a recommended method of euthanasia for sows and boars by the AVMA due to the method's efficacy and low costs, in addition to safety advantages over firearms, although the method has not yet been validated as an effective single-step method of euthanasia for these animals (AVMA, 2020).

PCB, along with other physical methods of euthanasia, present a serious problem as pigs mature (Anderson et al., 2019). The Humane Slaughter Association (HSA) described pigs as one of the most difficult species to effectively stun with a PCB, in part due to the smaller target area of the brain compared to other species and in part due to the location of the brain beyond the sinus cavities in pigs (HSA, 2013), so it is logical to conclude that pigs are also a difficult species to euthanize with a PCB. In mature sows and boars, a PCB may fail to penetrate the brain cavity because of more expansive developed sinus cavities and bony ridge along the front of the skull (HSA, 2013; Woods et al., 2010). Additionally, ensuring correct aim and direction of PCB placement may be difficult for mature sows and boars as a result of the variety of forehead face shapes in these animals (EFSA, 2020). The NPB and AASV recognized that PCB may only be sufficient to stun, and not euthanize, pigs as they mature due to the increased cranial thickness, along with the developed sinus cavities and bony ridge previously described (NPB and AASV, 2016). Ultimately, the correct placement of the PCB is critical to ensure a loss of consciousness is achieved following application of the PCB for all swine (EFSA, 2004). Further, incorrect PCB placement may not result in a loss of consciousness and result in a compromised welfare state (EFSA, 2020). In particular, correct placement of the PCB is especially important to ensure a loss of consciousness and subsequent death in mature sows and boars (NPB and AASV, 2016), where anatomical features complicate the process.

Anderson et al. (2019) concluded that the frontal PCB placement was more reliable and had fewer risks than the behind the ear placement for the euthanasia of market weight pigs, as indicated by a higher incidence of the bolt contacting the brain in heads shot in the frontal location. Further, refinement of the behind the ear placement was described as necessary to ensure reliability in practice (Anderson et al., 2019). Although the temporal PCB placement was described by the AVMA (AVMA, 2013) there have not been any previous attempts to validate that placement for growing pigs or mature breeding animals.

Our results suggest that the FRONTAL PCB placement may provide a bolt path with less tissue to travel through than either the TEMPORAL or BEHIND EAR PCB placements for sows and boars over 200 kg. It must be noted that cadaver heads were used in this study, so conclusions related directly to the efficacy of a single PCB placement cannot be made; however this information should be used to guide future research related to PCB placement and PCB device selection for mature sows and boars. All cadaver heads utilized in this study were observed to have the expansive sinus cavities that are typical of mature sows and boars (HSA, 2013; NPB and AASV, 2016; Woods et al., 2010).

This study was intended to serve as a step in the scientific validation of the TEMPORAL and BEHIND EAR PCB placements as alternatives to the common FRONTAL placement. Of the three PCB placements evaluated in this study, the FRONTAL placement appears to be the most reliable at this time with the PCB tool that we used. The reliability of the FRONTAL placement over the TEMPORAL and BEHIND EAR placements was indicated by the least tissue for the bolt to travel through, the greatest potential target area, and the greatest observed prevalence of brain damage. Future studies related to the TEMPORAL and BEHIND EAR alternative placements are warranted, as are studies related to the capacity of various PCB devices to reach and disrupt brain tissue. Some PCB tools may not be able to consistently reach the brain depending on bolt travel distance. The FRONTAL placement may present the least risk for the PCB euthanasia of sows and boars weighing 200 kg or more with the PCB used in this study at this time.

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Table 1. Tissue parameters of cadaver heads from mature sows and boars (BW > 200 kg) assigned to three penetrating captive bolt (PCB) placement treatments[1] and sectioned by band saw following the plane of bolt entry.

Dependent Variable	PCB Placement Treatment						Pooled SE	*P* - value
	FRONTAL		TEMPORAL		BEHIND EAR			
	SEM	n	SEM	n	SEM	n		
SOWS AND BOARS								
Soft tissue thickness, mm	6.0^{c}	58	51.7^{b}	48	59.2^{a}	41	1.4	< 0.0001
Cranial thickness, mm	41.0^{a}	58	19.8^{c}	48	30.9^{b}	41	1.5	< 0.0001
Total tissue thickness, mm	47.0^{c}	58	71.5^{b}	48	90.1^{a}	41	1.3	< 0.0001
Cross sectional brain area, mm^2	4194.4^{a}	39	1546.2^{c}	49	2618.7^{b}	51	160.3	< 0.0001
SOWS ONLY								
Soft tissue thickness, mm	5.6^{c}	42	52.2^{b}	34	59.1^{a}	29	1.5	< 0.0001
Cranial thickness, mm	47.1^{a}	42	17.6^{c}	34	30.2^{b}	29	1.4	< 0.0001
Total tissue thickness, mm	52.7^{c}	42	69.8^{b}	34	89.3^{a}	29	1.3	< 0.0001
Cross sectional brain area, mm^2	4330.5^{a}	27	1876.5^{c}	34	2769.8^{b}	37	199.8	< 0.0001
BOARS ONLY								
Soft tissue thickness, mm	6.4^{c}	16	51.1^{b}	14	59.3^{a}	12	2.1	< 0.0001
Cranial thickness, mm	34.8^{a}	16	22.1^{b}	14	31.6^{ab}	12	3.2	0.0165
Total tissue thickness, mm	41.2^{c}	16	73.2^{b}	14	90.9^{a}	12	2.4	< 0.0001
Cross-sectional brain area, mm^2	4058.4^{a}	12	1216.0^{c}	15	2467.5^{b}	14	130.5	< 0.0001

[1] Treatments: FRONTAL – Medial bolt entry approximately 3.5 cm superior to a line across the top of both eyes and perpendicular with the external surface of the head; TEMPORAL – Bolt entry at the depression located between the right eye and right ear. BEHIND EAR – Bolt entry directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye.
[a,b,c] Superscripts that differ identify significant differences between means within dependent variables across treatments ($P \leq 0.05$).

Table 2. Brain damage of cadaver heads from mature sows and boars (BW > 200 kg) assigned to three penetrating captive bolt (PCB) placement treatments[1] and sectioned by band saw following the plane of bolt entry.

Dependent Variable	PCB Placement Treatment				
	Damage Detected	Total	Percentage	Lower 95% Confidence Interval	Upper 95% Confidence Interval
SOWS AND BOARS					
FRONTAL	41	42	97.62%	87.43%	99.94%
TEMPORAL	26	55	47.27%	33.65%	61.20%
BEHIND EAR	15	54	27.78%	16.46%	41.64%
TOTAL	82	151	54.30%	46.01%	62.43%
SOWS ONLY					
FRONTAL	29	30	96.67%	82.78%	99.92%

TEMPORAL	21	37	56.76%	39.49%	72.90%
BEHIND EAR	6	40	15.00%	5.71%	29.84%
TOTAL	56	107	52.34%	42.46%	62.08%
BOARS ONLY					
FRONTAL	12	12	100.00%	73.54%	100.00%
TEMPORAL	5	18	27.78%	9.69%	53.48%
BEHIND EAR	9	14	64.29%	35.14%	87.24%
TOTAL	26	44	59.09%	43.25%	73.66%

[1] Treatments: FRONTAL – Medial bolt entry approximately 3.5 cm superior to a line across the top of both eyes and perpendicular with the external surface of the head; TEMPORAL – Bolt entry at the depression located between the right eye and right ear; BEHIND EAR – Bolt entry directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye.

Table 3. Data regarding brain damage of cadaver heads from mature sows and boars (BW > 200 kg) assigned to three penetrating captive bolt (PCB) placement treatments[1] and sectioned by band saw following the plane of bolt entry.

	PCB Placement Treatment				
Dependent Variable					
	Damage Detected	Total	Percentage	Lower 95% Confidence Interval	Upper 95% Confidence Interval
FRONTAL					
Frontal lobe	23	42	54.76%	38.76%	70.15%
Parietal lobe	41	42	97.62%	87.43%	99.94%
Temporal lobe	0	42	0.00%	0.00%	8.41%
Occipital lobe	34	42	80.95%	65.88%	91.40%

Corpus callosum	37	42	88.10%	74.37%	96.02%
Diencephalon	18	42	42.86%	27.72%	59.04%
Mesencephalon	1	42	2.38%	0.06%	12.57%
Brainstem	1	42	2.38%	0.06%	12.57%
Cerebellum	2	42	4.76%	0.58%	16.16%
TEMPORAL					
Frontal lobe	0	55	0.00%	0.00%	6.49%
Parietal lobe	30	55	54.55%	40.55%	68.03%
Temporal lobe	10	55	18.18%	9.08%	30.90%
Occipital lobe	1	55	1.82%	0.05%	9.72%
Corpus callosum	6	55	10.91%	4.11%	22.25%
Diencephalon	0	55	0.00%	0.00%	6.49%
Mesencephalon	0	55	0.00%	0.00%	6.49%
Brainstem	0	55	0.00%	0.00%	6.49%
Cerebellum	0	55	0.00%	0.00%	6.49%
BEHIND EAR					
Frontal lobe	0	54	0.00%	0.00%	6.60%
Parietal lobe	11	54	20.37%	10.63%	33.53%
Temporal lobe	7	54	12.96%	5.37%	24.90%
Occipital lobe	11	54	20.37%	10.63%	33.53%
Corpus callosum	5	54	9.26%	3.08%	20.30%
Diencephalon	1	54	1.85%	0.05%	9.89%
Mesencephalon	0	54	0.00%	0.00%	6.60%
Brainstem	0	54	0.00%	0.00%	6.60%
Cerebellum	0	54	0.00%	0.00%	6.60%

[1] Treatments: FRONTAL – Medial bolt entry approximately 3.5 cm superior to a line across the top of both eyes and perpendicular with the external surface of the head; TEMPORAL – Bolt entry at the depression located between the right eye and right ear; BEHIND EAR – Bolt entry directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye.

Table 4. Data regarding brain damage of cadaver heads from mature sows (BW > 200 kg) assigned to three penetrating captive bolt (PCB) placement treatments[1] and sectioned by band saw following the plane of bolt entry.

Dependent Variable	PCB Placement Treatment				
	Damage Detected	Total	Percentage	Lower 95% Confidence Interval	Upper 95% Confidence Interval
FRONTAL					
Frontal lobe	15	30	50.00%	31.30%	68.70%
Parietal lobe	29	30	96.67%	82.78%	99.92%
Temporal lobe	0	30	0.00%	0.00%	11.57%
Occipital lobe	24	30	80.00%	61.43%	92.29%

Corpus callosum	25	30	83.33%	65.28%	94.36%
Diencephalon	13	30	43.33%	25.46%	62.57%
Mesencephalon	1	30	3.33%	0.08%	17.22%
Brainstem	0	30	0.00%	0.00%	11.57%
Cerebellum	1	30	3.33%	0.08%	17.22%
TEMPORAL					
Frontal lobe	0	37	0.00%	0.00%	9.49%
Parietal lobe	25	37	67.57%	50.21%	81.99%
Temporal lobe	9	37	24.32%	11.74%	41.20%
Occipital lobe	1	37	2.70%	0.07%	14.16%
Corpus callosum	5	37	13.51%	4.54%	28.77%
Diencephalon	0	37	0.00%	0.00%	9.49%
Mesencephalon	0	37	0.00%	0.00%	9.49%
Brainstem	0	37	0.00%	0.00%	9.49%
Cerebellum	0	37	0.00%	0.00%	9.49%
BEHIND EAR					
Frontal lobe	0	40	0.00%	0.00%	8.81%
Parietal lobe	4	40	10.00%	2.79%	23.66%
Temporal lobe	3	40	7.50%	1.57%	20.39%
Occipital lobe	5	40	12.50%	4.19%	26.80%
Corpus callosum	2	40	5.00%	0.61%	16.92%
Diencephalon	1	40	2.50%	0.06%	13.16%
Mesencephalon	0	40	0.00%	0.00%	8.81%
Brainstem	0	40	0.00%	0.00%	8.81%
Cerebellum	0	40	0.00%	0.00%	8.81%

[1] Treatments: FRONTAL – Medial bolt entry approximately 3.5 cm superior to a line across the top of both eyes and perpendicular with the external surface of the head; TEMPORAL – Bolt entry at the depression located between the right eye and right ear; BEHIND EAR – Bolt entry directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye.

Table 5. Data regarding brain damage of cadaver heads from mature boars (BW > 200 kg) assigned to three penetrating captive bolt (PCB) placement treatments[1] and sectioned by band saw following the plane of bolt entry.

Dependent Variable	PCB Placement Treatment				
	Damage Detected	Total	Percentage	Lower 95% Confidence Interval	Upper 95% Confidence Interval
FRONTAL					
Frontal lobe	8	12	66.67%	34.89%	90.08%
Parietal lobe	12	12	100.00%	73.54%	100.00%
Temporal lobe	0	12	0.00%	0.00%	26.46%

Occipital lobe	10	12	83.33%	51.59%	97.91%
Corpus callosum	12	12	100.00%	73.54%	100.00%
Diencephalon	5	12	41.67%	15.17%	72.33%
Mesencephalon	0	12	0.00%	0.00%	26.46%
Brainstem	1	12	8.33%	0.21%	38.48%
Cerebellum	1	12	8.33%	0.21%	38.48%
TEMPORAL					
Frontal lobe	0	18	0.00%	0.00%	18.53%
Parietal lobe	5	18	27.78%	9.69%	53.48%
Temporal lobe	1	18	5.56%	0.14%	27.29%
Occipital lobe	0	18	0.00%	0.00%	18.53%
Corpus callosum	1	18	5.56%	0.14%	27.29%
Diencephalon	0	18	0.00%	0.00%	18.53%
Mesencephalon	0	18	0.00%	0.00%	18.53%
Brainstem	0	18	0.00%	0.00%	18.53%
Cerebellum	0	18	0.00%	0.00%	18.53%
BEHIND EAR					
Frontal lobe	0	14	0.00%	0.00%	23.16%
Parietal lobe	7	14	50.00%	23.04%	76.96%
Temporal lobe	4	14	28.57%	8.39%	58.10%
Occipital lobe	6	14	42.86%	17.66%	71.14%
Corpus callosum	3	14	21.43%	4.66%	50.80%
Diencephalon	0	14	0.00%	0.00%	23.16%
Mesencephalon	0	14	0.00%	0.00%	23.16%
Brainstem	0	14	0.00%	0.00%	23.16%
Cerebellum	0	14	0.00%	0.00%	23.16%

[1] Treatments: FRONTAL – Medial bolt entry approximately 3.5 cm superior to a line across the top of both eyes and perpendicular with the external surface of the head; TEMPORAL – Bolt entry at the depression located between the right eye and right ear; BEHIND EAR – Bolt entry directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye.

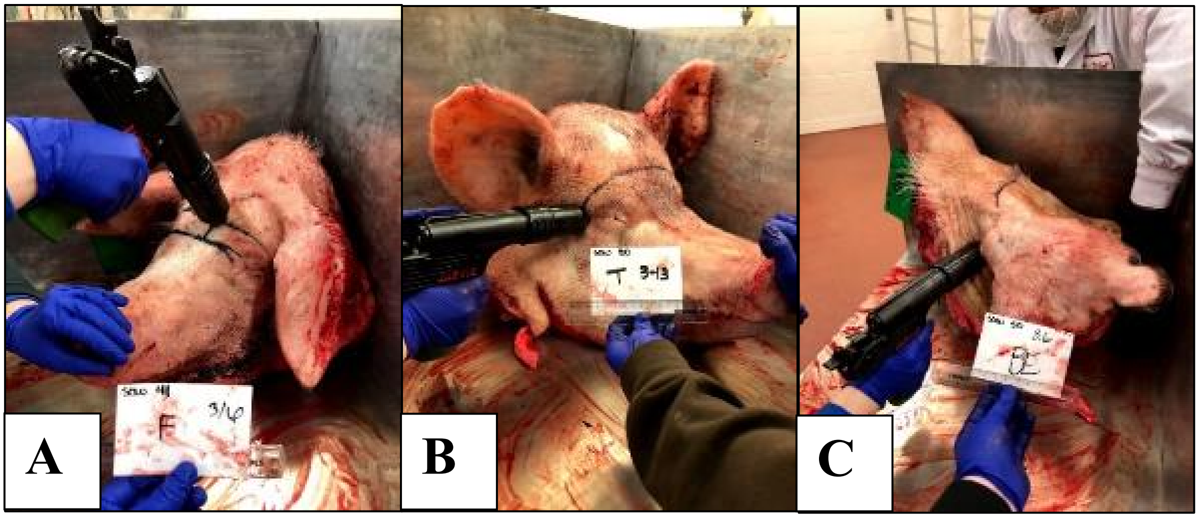

Figure 1. Penetrating captive bolt (PCB) placement treatments. (A) FRONTAL – shot placed 3.5 cm superior to a line drawn across the eyes at midline; (B) TEMPORAL – shot placed at the depression posterior to the lateral canthus of the eye within the plane between the lateral canthus and the base of the ear; (C) BEHIND EAR – shot placed directly caudal to the pinna of the ear on the same plane as the eyes and targeting the middle of the opposite eye.

Figure 2. Relationship of frontal cranial thickness (mm) and maximum deflection distance (cm) between a straight line from snout to poll and the frontal surface of cadaver heads from sows >200 kg LW (n = 19).

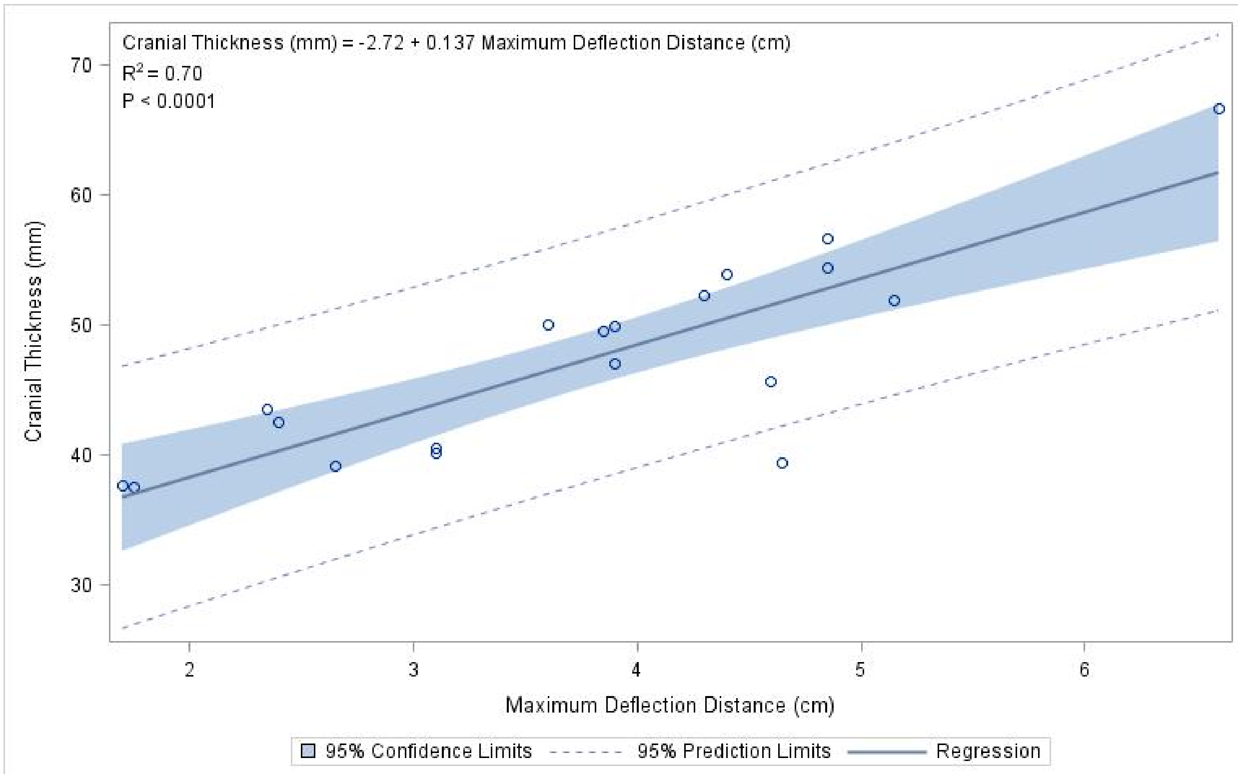

Figure 3. Relationship of total frontal tissue thickness (mm) and maximum deflection distance (cm) between a straight line from snout to poll and the frontal surface of cadaver heads from sows >200 kg LW (n = 19).

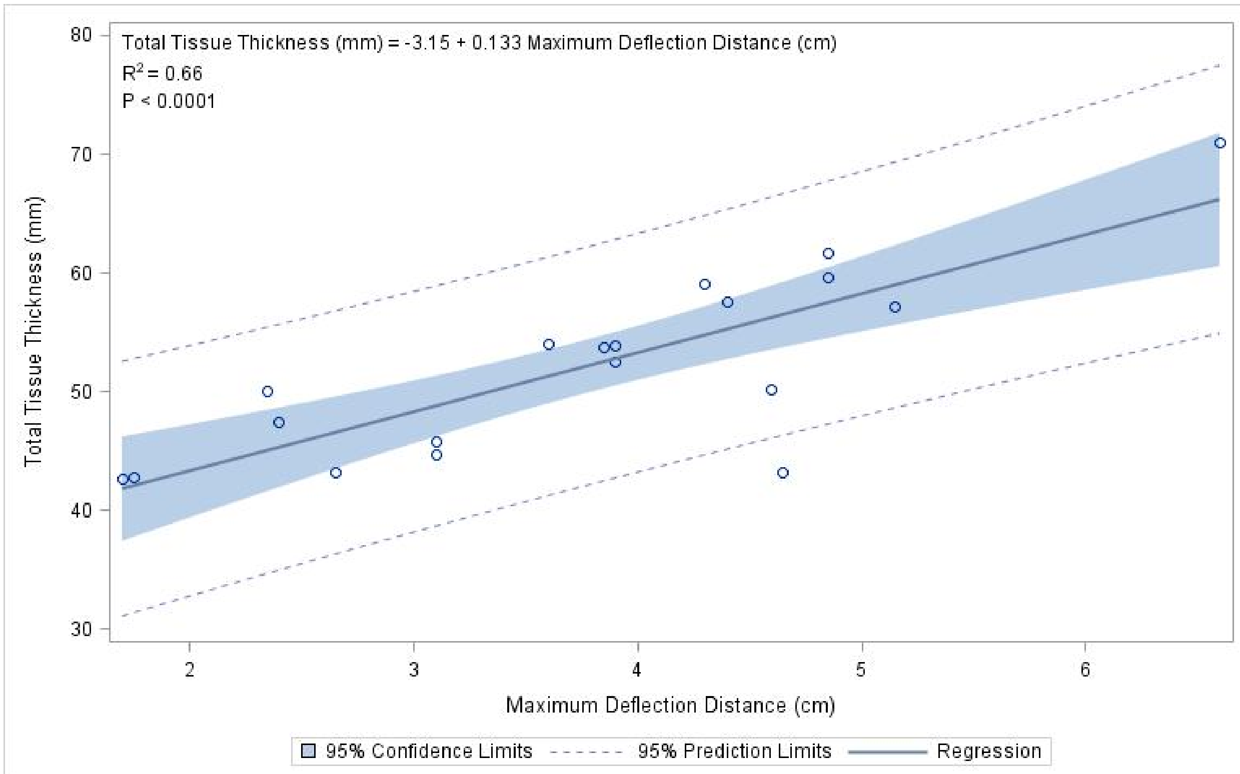

Figure 4. Relationship of cranial thickness (mm) and weight (kg) of cadaver heads from sows >200 kg LW (n = 42).

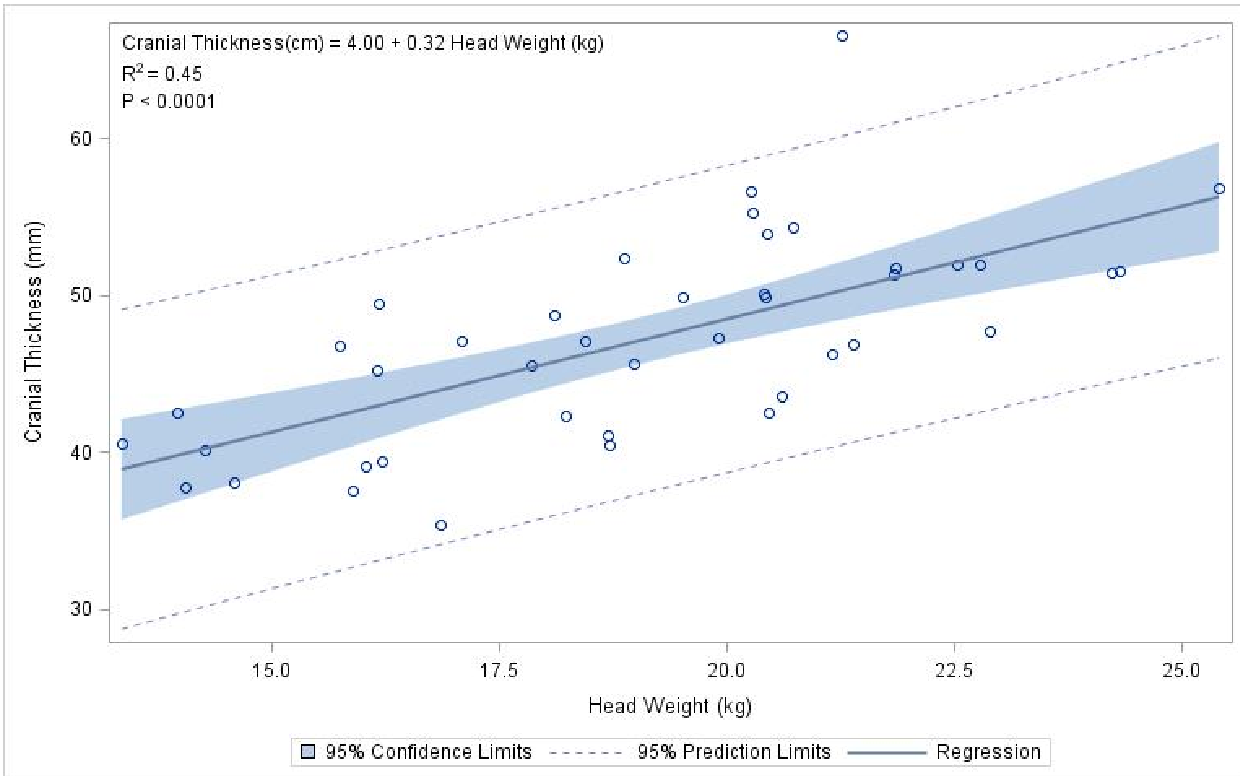

Figure 5. Relationship of total frontal tissue thickness (mm) and weight (kg) of cadaver heads from sows >200 kg LW (n = 42).