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Using post-mortem computed tomography to identify traumatic cranial lesions in small stranded odontocetes euthanised via ballistics

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ABSTRACT

Aims: To describe the pathophysiology caused by ballistics applied to the head of stranded cetaceans that required euthanasia and use this information to infer the likely welfare implications of these real-life euthanasia events.

Methods: Post-mortem computed tomography (PMCT) imaging was conducted on six cetacean carcasses of five different species that were submitted for dissection following ballistics euthanasia. No animals were euthanised for the purpose of this study. All data were collected opportunistically at stranding events where euthanasia was *a priori* deemed necessary by the Department of Conservation (DOC) in partnership with indigenous Māori (iwi). The cranial damage assessed included osseous lesions at entry and exit wounds, intracranial bone fractures and intracranial projectile fragments. Potential welfare implications were inferred based on the likelihood of instantaneous insensibility occurring due to direct physical disruption to the brainstem. Additionally, basic stranding data were collected from DOC incident reports including whether animals were refloated prior to the decision for euthanasia. We also gathered information from the marksperson involved on how the ballistics method was employed, equipment used, and animal insensibility assessed at each stranding event.

Results: PMCT results suggest that two animals were likely instantaneously insensible, three had a moderate chance of being instantly insensible and one had a low chance of instantaneous insensibility. In one case, the marksperson reported a faster time to insensibility/death than was judged likely to have occurred from PMCT. In only two cases were the criteria for verifying insensibility reported as being checked. The likelihood of instantaneous insensibility occurring was affected by shot placement/aim and characteristics of the projectile used.

Conclusions: Euthanasia is a critical option for severely compromised cetaceans. While most animals examined were probably rapidly insensible following shooting, cranial trauma and thus confidence in the efficacy of ballistics seemed to vary with shot placement, aim, equipment and cranial anatomy.

Clinical relevance: Verification of insensibility immediately following shooting, by assessing reflex responses as recommended, is crucial to ensure humane emergency management. PMCT provides an effective non-destructive tool to validate field methods for assessing the efficacy of euthanasia.

Abbreviations: DOC: Department of Conservation Te Papa Atawhai; HU: Hounsfield units; PMCT: Post-mortem computed tomography; SOP: Standard operating procedure; TTI/D: Time to insensibility or death

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Animal welfare; euthanasia; cetacean; computed tomography; insensibility

Introduction

In the context of emergency management of wild animals, euthanasia (humane killing) is a key tool for preventing or ending suffering (Leary *et al.* 2020). There is no single accepted definition of euthanasia. Following American Veterinary Medical Association guidelines, here we consider euthanasia as the use of humane techniques to induce the most rapid, painless and distress-free death possible (Leary *et al.* 2020). Live stranding of cetaceans (whales, dolphins and porpoises) constitutes a wild animal emergency and is becoming increasingly common, particularly in Aotearoa New Zealand (Betty *et al.* 2020; Boys *et al.* 2021). While attempts may be made to refloat live-stranded cetaceans, their often-debilitated state and severely compromised welfare mean animals may

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not survive even if refloated, and so euthanasia is recommended for a better welfare outcome.

Practical methods for euthanasia in emergency field situations are often limited by access to the animals, equipment, resourcing, human safety and legal restrictions (Leary *et al.* 2020). In NZ, ballistics is the only technique employed for euthanasia of stranded cetaceans due to logistical constraints, human safety and environmental contamination (see Boys *et al.* 2021, 2022 for specific details). The decision to euthanise, and the action of euthanasia itself, is undertaken by warranted officers of the NZ Department of Conservation Te Papa Atawhai (DOC; management agency with legal jurisdiction at strandings), following discussion with iwi (local indigenous Māori). DOC uses a standard operating procedure (SOP) to guide decision-making at strandings, including the process of employing ballistics euthanasia (Boren 2012).

Euthanasia via ballistics can render an animal immediately insensible if employed appropriately. It is generally understood that for ballistics to result in permanent insensibility, the brainstem should be significantly disrupted or destroyed (Millar and Mills 2000; Parvizi and Damasio 2003; DeNicola *et al.* 2019). Damage to the cerebrum or spinal cord only may not cause instantaneous insensibility and could leave the animal severely wounded but aware, resulting in significant negative welfare impacts (Grady *et al.* 2022; Taran *et al.* 2023). Therefore, it is vital that appropriate anatomical targets are identified, and accurate aim employed. Aside from these elements, factors related to the firearm and projectile can also influence the potential for insensibility due to the severity of tissue disruption or wounding that may occur (Thali *et al.* 2003; Hampton *et al.* 2016).

Understanding the severity and location of intracranial damage caused by ballistics can provide information on the impacts on animal welfare before death (Thomson *et al.* 2013; Lund *et al.* 2021). Specifically, this kind of information can indicate the likelihood that the animal has been rendered rapidly insensible, and in cases where this may not have occurred, contribute to understanding potential animal welfare concerns. The subfield of wounding ballistics examines the tissue injuries caused by a projectile and is, therefore, particularly important in understanding the welfare impacts of euthanasia for emergency management of stranded cetaceans (Øen and Knudsen 2007; Hampton *et al.* 2014; Boys *et al.* 2024). In human forensics, the use of radiology, specifically, imaging modalities such as CT, has commonly been applied to identify osseous lesions and ballistics trajectories in cases of gunshot wounds to the head (Thali *et al.* 2003; Abdul Rashid *et al.* 2013; Del Fante *et al.* 2019).

Similar approaches have been used to assess the humaneness of killing methods in animals such as cattle (Thomson *et al.* 2013; Schwenk *et al.* 2016). In particular, the effectiveness of cranial ballistics for euthanasia has been evaluated using CT by identifying entry and exit wounds, wound tracks, intracranial bone splinters and lesions in brain tissue (e.g. Thomson *et al.* 2013; Lund *et al.* 2021; Boys *et al.* 2024). This is important since it is not uncommon for projectile trajectories to alter on impact with the skull, which could lead to ineffective tissue damage (Millar and Mills 2000) and suboptimal welfare outcomes. While it is possible for insensibility to occur due to concussive shock from a misaligned projectile, this is less likely to cause sufficient brainstem disruption to lead to permanent insensibility, and animals may regain consciousness (Grandin 2002).

Despite the common use of ballistics at cetacean stranding events, there remains limited empirical evidence on appropriate procedures, firearm calibres and projectiles to achieve euthanasia (i.e. death that minimises negative welfare impacts) (Hampton *et al.* 2014; Boys *et al.* 2022, 2024). Research from NZ has also highlighted concerns around the limited verification of insensibility following the application of ballistics. This is despite verification being vital to understand the duration of awareness and potential negative welfare impacts (Mellor and Littin 2004; Leary *et al.* 2020) and being explicitly required in DOC's SOP via the testing of palpebral and corneal reflexes (Boys *et al.* 2023, 2024, 2025).

Using opportunistic post-mortem CT (PMCT), this study aims to describe the pathophysiology caused by ballistics applied to the head of stranded cetaceans that required euthanasia to infer the likely welfare implications. Specifically, we use PMCT to describe the shot placement and the cranial damage achieved. By examining projectile entry and exit sites, intracranial fragments, projectile tracks and the relationship with skull and brain structures, we interpret the likelihood of causing instantaneous insensibility based on disruption to key brain structures, particularly the brainstem. To contextualise the cranial disruption observed and highlight potential welfare concerns, we gathered additional information from the marksperson who shot the animal in each case about the method of application and equipment used and qualitative data reflecting their assessment of insensibility following shooting.

Materials and methods

No animals were euthanised for the purpose of this study. All data were collected opportunistically where euthanasia was *a priori* deemed necessary by DOC in partnership with iwi. This project was evaluated by the Massey University Animal Ethics Committee and approved under notification numbers 20/10 and 20/27. The project was also evaluated by the Massey

University Human Ethics Committee and approved under notification number NOR 20/53. Research permits from DOC were approved following iwi consultation, under permit number 39239-MAR. In alignment with permission NOR 20/53 from the Massey University Human Ethics Committee, the raw data from this study must remain confidential owing to its sensitive nature. The study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Basic stranding data were collected from DOC incident reports, including whether animals were refloated prior to a decision of euthanasia being made. Additionally, a set of questions was sent electronically to the marksperson involved in the euthanasia to gather information on how the ballistics method was employed, equipment used, and assessment of the animal's insensibility at each stranding event (see Supplementary Material). Specifically, we requested qualitative data from the marksperson on the type and calibre of the firearm, the type and grain of the projectile, the anatomical landmarks used to aim, angle of the shot (dorso-ventral or lateral; Blackmore *et al.* 1995; IWC 2006), whether (from their perspective) insensibility/death criteria were assessed and if so, which these were, how assessments were made, and the perceived time to insensibility/death of the animal. Markspersons were also given the opportunity to provide any additional comments if they wished. These data were considered alongside the PMCT findings to provide further context to the ballistics procedure and highlight any potential welfare concerns.

Post-mortem computed tomography imaging was conducted on six cetacean carcasses of five different species that were submitted for dissection. These were two bottlenose dolphins (*Tursiops truncatus*), a dusky dolphin (*Lagenorhynchus obscurus*), a common dolphin (*Delphinus delphis*), a false killer whale (*Pseudorca crassidens*) and a pygmy sperm whale (*Kogia breviceps*). At PMCT, one carcass (common dolphin) was whole, allowing for imaging of the cranial and thoracic regions, whilst the other carcasses had undergone prior disarticulation and only the heads were available for imaging. Following PMCT, three of the heads (bottlenose dolphin 1, common and dusky dolphins) were dissected to corroborate gross lesions with PMCT findings; the other three could not be further dissected due to cultural reservations.

Following application of ballistics, all carcasses were frozen (−20°C) within a few hours and transported to the dissection facility. Where necessary, carcasses were dissected caudal to the projectile entry wound to enable the head to remain frozen until imaging could be undertaken. Dissection of carcasses followed standard protocols (IJsseldijk *et al.* 2019) and included biological data collection on sex, total body length, maturity status and qualitative body condition based on blubber thickness. These data were considered alongside PMCT results and information on the euthanasia method to provide additional context.

Table 1. Parameters of post-mortem computed tomography scans[a] of cetacean carcasses submitted following ballistics euthanasia after stranding.

Species	kV	mA	Pitch	Slice thickness (mm)
Bottlenose dolphin (*Tursiops truncatus*) 1	130	190	0.95	0.75
Dusky dolphin (*Lagenorhynchus obscurus*)	130	150	0.75	0.75
Common dolphin (*Delphinus delphis*)	130	23	0.95	0.75
Bottlenose dolphin (*Tursiops truncatus*) 2	130	120	1.0	0.80
Pygmy sperm whale (*Pseudorca crassidens*)	130	185	1.0	2.0
False killer whale (*Kogia breviceps*)	130	120	1.0	0.80

[a]Multi-slice spiral CT scanner (SOMATOM; Siemens Healthineers, Erlangen, Germany).

The frozen carcasses were scanned following Kot *et al.* (2020) in the prone position. PMCT scanning was optimised to minimise metallic artefacts, and an extended CT scale was used to delineate between dense, hyperattenuating cetacean bones and metal, and reduce high-attenuation artefacts (Link *et al.* 2000; Fraga-Manteiga *et al.* 2014). All animals were scanned using a multi-slice spiral CT scanner (SOMATOM; Siemens Healthineers, Erlangen, Germany), with parameters varying slightly to ensure the highest quality images (Table 1). CT images were reviewed using commercially available DICOM viewing software (Horos; Horosproject.org and RadiAnt DICOM Viewer; Medixant, Poznań, Poland). Multiplanar reconstruction was used to generate transverse, sagittal and dorsal plane reconstructions with adjustments to windowing and levelling as needed during interpretation.

All PMCT data were reconstructed and interpreted by a diagnostic imaging researcher (BCWK) and a final-year veterinary diagnostic imaging resident (GL). The radiological focus was on the cranial damage, including any osseous lesions at the entry and exit wounds, intracranial bone fractures through the trajectory path, and intracranial metallic fragments from the projectile. Potential welfare implications were inferred based on the likelihood of instantaneous insensibility occurring due to direct physical disruption to the brainstem, spinal cord, first cervical vertebra, and occipital condyles (Boys *et al.* 2024).

Results

Bottlenose dolphin 1

From the DOC incident report, the bottlenose dolphin stranded and was refloated twice. However, the animal

Table 2. Summary of biological data from cetacean carcasses submitted following ballistics euthanasia after stranding, and details of the ballistics equipment and shot application for euthanasia. Firearm and projectile equipment, and approach and location of shot are those reported by the marksperson who performed the euthanasia, while the angle was reported and confirmed by post-mortem computed tomography (PMCT).

	Biological data on individual			Equipment information		Shot application(s)		
Species	Sex	Length (cm)	BCS	Firearm	Projectile (n, weight and construction)	Approach (reported)	Location (reported)	Angle (reported and PMCT)
Bottlenose dolphin (*Tursiops truncatus*) 1	F	250	Mod – poor	.357 rifle	1, 158 gr, soft round-nose	DV	6.5 cm caudal to blowhole	Directly down ~ 90°
Dusky dolphin (*Lagenorhynchus obscurus*)	M	156	Good	.223 rifle	1, 65 gr, soft point	Lateral	8 cm caudal to eye	Directly across ~ 90°
Common dolphin (*Delphinus delphis*)	F	185	Mod – poor	.308 rifle	2, 150 gr, soft point	DV	Shot 1: 13.2 cm caudal to blowhole Shot 2: 18.7 cm caudal to blowhole	Directly down ~ 90°
Bottlenose dolphin (*Tursiops truncatus*) 2[a]	F	298	Unk	30-06 rifle	2, 140 gr, soft point	Lateral	8 cm caudal to eye	Angled caudo-ventrally
False killer whale (*Pseudorca crassidens*)[a]	Unk	Unk	Unk	30-06 rifle	1, 140 gr, soft point	DV/lateral	Blowhole used as landmark	Angled caudally
Pygmy sperm whale (*Kogia breviceps*)	F	181	Mod	30-06 rifle	1, 180 gr, solid slug	Lateral	8.5 cm caudal to eye	Directly across ~ 90°

[a]Only the head of the animal was available for assessment.
BCS = body condition score; DV = dorso-ventral; F = female; gr = grain; M = male; Mod = moderate; Unk = unknown.

was unable to remain upright and on re-stranding, the decision was made to euthanise the animal. A single dorso-ventral shot was applied using a .357 rifle with a 158-grain, soft, round-nose projectile (Table 2). An entry wound caudal to the blowhole was evident, though no exit wound was observed. The marksperson aimed using "*the crease at the back of the skull when pulling the jaw up slightly*," and when asked about time to death, stated that it was instantaneous based on there being "*no further movements following the shot*."

The head had been excised at the level of the first and second thoracic vertebrae. The trajectory of the shot on the PMCT scan suggested that firearm discharge was dorso-ventral (Figure 1). The projectile entry wound was 6.5 cm caudal to the blowhole, aimed directly down towards the ventrum (~ 90°), entering the cranial cavity through the suture between the frontal and interparietal bone. The left parietal bone was fractured at the level of the nasal cavity, extending caudally towards the interparietal bone on the dorsal side. Comminuted fractures of the interparietal and supraoccipital bones around the entry wound were noted, with bone fragments observed within the cerebrum. The falx cerebri was also fractured, with the fracture extending bilaterally and caudally to the exoparietal bones. The cervical vertebrae remained intact with no significant findings.

Multiple metal-attenuating foci (> 2,500 Hounsfield units; HU), interpreted as projectile fragments, were distributed peripheral to the entry wound, associated with the comminuted fracture in the cranium. These fragments formed a semi-linear pattern and disrupted the cerebrum alongside the bone fragments. Several larger metal-attenuating fragments were deposited close to the ventral aspect of the cranium. However, no fractures were evident in the basisphenoid or basioccipital bones.

On dissection, bone and metallic projectile fragments were located within brain parenchyma, but the brainstem remained intact. On extraction of the brain from the calvarium, fractures were noted in the supraoccipital bone, particularly surrounding the entry wound, although no damage was observed at the atlanto-occipital joint, and the occipital condyles remained intact (Table 3).

Dusky dolphin

From the DOC incident report, the stranded dusky dolphin was originally refloated, although it was unable to remain upright and swam in tight circles. As the animal re-stranded on rocks and the tide was outgoing, the decision was made by DOC to euthanise it. A single lateral shot was applied using a .223 rifle and a 65-grain soft-point projectile "*on the side of the head between the eye and pectoral fin*" (Table 2). No external exit wound was present on the contralateral side. The marksperson felt "[…] *confident death was instantaneous*" since there was "*no nervous twitching, no breathing*."

The head had been excised at the level of the fused cervical vertebrae (C1 – C2). On PMCT, the entry wound on the right lateral side was at the level of the temporal fossa, with the projectile entering the cranial cavity via the parietal bone. Some small, hyperattenuating (> 250 HU) fragments, likely bone, were noted in the blubber on the contralateral side (Figure 2).

Multiple, highly comminuted fractures were present throughout the entire skull. The greatest degree of displaced comminuted fragments was centred on the supraoccipital bone. Comminuted fractures extended

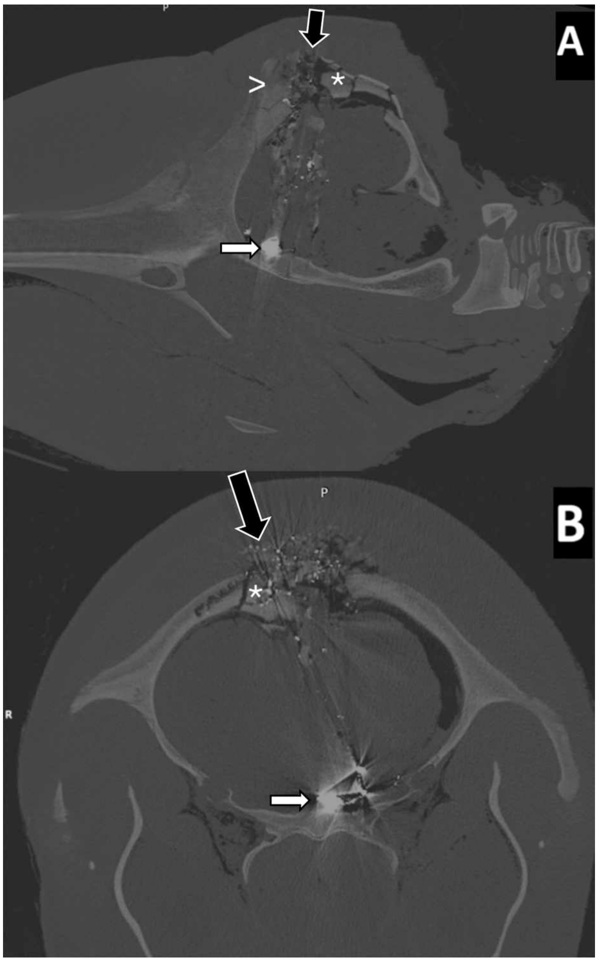

Figure 1. Multiplanar (A) parasagittal and (B) transverse reconstruction CT of the head of bottlenose dolphin (*Tursiops truncatus*) 1 in a high-frequency algorithm with an extended CT window (window width: 9,000 HU; window level: 2,000 HU) showing the entry wound at the dorsal aspect of the calvarium (black arrows) and the metal projectile resting along the ventral aspect of the calvarium (white arrows). The nasal bone (>) and fractured frontal bone (*) are indicated. These illustrate the dorso-ventral approach with slight rostral and left lateral deviation of the projectile.

to the occipital condyles with multiple, highly comminuted fragments present in the region of the left occipital condyle. The parietal bones also exhibited severe comminuted fractures with moderate displacement. Multiple fractures were also noted on the first cervical vertebra. A large surface defect was present along the right lateral side of the head, at the level of the parietal bones, with metallic artefacts traversing across to the corresponding left lateral side. More metal artefacts were present along the right side of the head. A large degree of variably sized, metal artefacts were present throughout the calvarium within the brain. Liquefaction of the brain was noted with gas accumulation dorsal to the dorsal calvarium. Both tympanic bullae exhibited severe comminuted fractures, and metal artefacts were also noted surrounding the left tympanic bulla. Some metallic fragments were also present within the left acoustic fat. Fluid, faint metal fragments and scant gas were present within the nasal canal.

On dissection, fractures were observed in the supraoccipital, parietal, frontal and basilar occipital bones. The brain parenchyma showed clear disruption, though minimal metallic fragments were collected. Both occipital condyles were found to be fractured (Table 3).

Common dolphin

Based on the DOC incident report, the stranded common dolphin was refloated four times before the decision to euthanise was made. Two dorso-ventral shots were applied "*a few seconds apart*" using a .308 rifle and .308 Winchester 150-grain soft-point projectiles (Table 2). The marksperson reportedly aimed "*halfway between the blowhole and the front of the pectoral fin*" on the dorsal midline, with the second shot

Table 3. Likelihood of instantaneous insensibility for six cetaceans subjected to ballistics euthanasia following stranding, estimated from pathophysiology revealed using post-mortem computed tomography (PCMT) and dissection when possible, and the reported time to insensibility/death (TTI/D) and indicators for TTI/D reported by the marksperson who performed euthanasia.

		Supporting evidence		
Species	Likelihood of instantaneous insensibility[a]	PMCT/gross pathology	Reported TTI/D	Reported indicators for TTI/D
Bottlenose dolphin (*Tursiops truncatus*) 1	Low	Brainstem intact	Instant	Absence of movement after shot
Dusky dolphin (*Lagenorhynchus obscurus*)	High	Fractures of occipital condyles, C1 and likely brainstem disruption	Instant	No nervous twitching, no breathing after shot
Common dolphin (*Delphinus delphis*)	High	Brainstem disrupted	1 second	No breathing, no movement after second shot
Bottlenose dolphin (*Tursiops truncatus*) 2	Moderate	Brain intact but brain tissue likely extruded	0–30 seconds	Big exhale and tapping of eye[b]
False killer whale (*Pseudorca crassidens*)	Moderate	Brain intact but fractures along occipital condyle	0–30 seconds	Big exhale and tapping of eye[b]
Pygmy sperm whale (*Kogia breviceps*)	Moderate	Brain intact but disruption to structures in proximity to brainstem	Instant	Unknown

[a]Estimated for the reported first shot (if more than one).
[b]"Tapping of eye" indicates testing of the corneal reflex, a criterion used to verify unconsciousness.
C1 = first cervical vertebra.

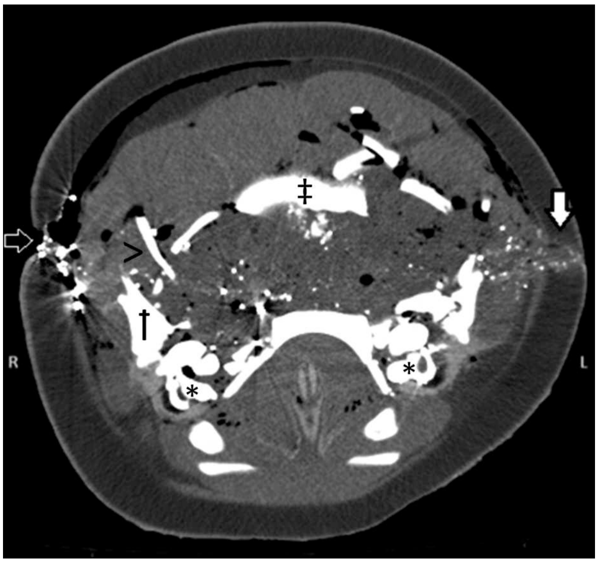

Figure 2. Transverse CT of dusky dolphin (*Lagenorhynchus obscurus)* head, in a soft tissue algorithm with a soft tissue window (window width: 400 HU; window level: 60 HU), showing the entry wound at the right lateral aspect of the head (black arrow), with numerous metal and bone fragments and overall extensive collapse of the calvarium. The white arrow indicates the exit wound along the left lateral aspect of the head with a trail of small metallic and bony fragments extending to the surface. The tympanic bullae (*), temporal bone (†), parietal bone (>) and occipital bone (‡) are indicated.

caudal to the first. The marksperson felt that death occurred in one second, stating that the "*animal went rigid for a split second and then went floppy.* […] *No additional movement in this animal after the second shot.* […] *Looked at its eyes, no breathing or any other movement. Animal totally unresponsive*."

The first and second entry wounds were 13.2 and 18.7 cm caudal to the blowhole on the dorsal midline, respectively (Figure 3). The trajectory of both shots on the PMCT suggests that firearm discharge was above the dorsal aspect of the animal, angled directly down towards the ventrum (~ 90°; Table 2). Both projectiles were considered partially 'through-and-through'; exit wounds to body regions outside the cranium were observed slightly medial and cranial to the right pectoral fin.

Multiple, highly comminuted fractures with variable fragment displacement involving the entire calvarium (frontal, parietal, temporal and occipital bones) were present. The greatest degrees of calvarial fractures were centred on the supraoccipital bone and occipital condyles. A large number of punctate, mineral-attenuating foci were present along the base of the occipital condyles with more metal foci present within the ventral soft tissues at the level of the first cervical vertebra. The right tympanic bulla was also fractured with minimal displacement. Multiple metal foci were present within the right tympanic bulla and adjacent to it.

A large surface defect was present dorsal to the cervical vertebra with abundant mineral-attenuating debris tracking through to the ventrum and terminating at the level of, and slightly right lateral to, the hyoid bones. Marked comminuted fractures of the cranial cervical to mid-cervical vertebrae were present as a result. A second, slightly smaller penetrating surface defect was seen caudally at the cervicothoracic region with a similar trail of metallic fragments terminating at the level of the sternal manubrium. There

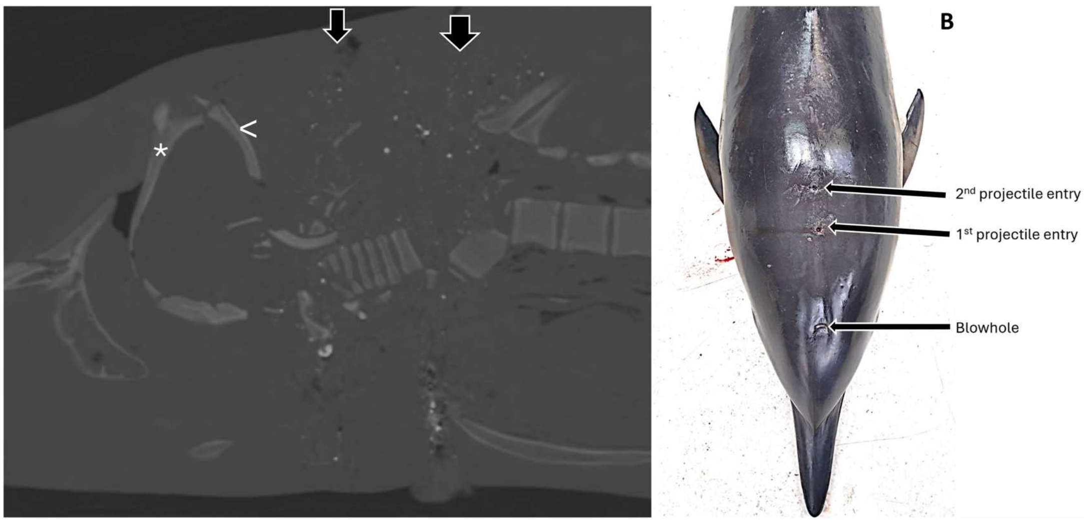

Figure 3. Images of a common dolphin (*Delphinus delphis*) that was shot twice from a dorso-ventral approach on the dorsal midline caudal to the blowhole. (A) Parasagittal multiplanar reconstruction CT in a high-frequency algorithm with an extended CT scale (window width: 9,000 HU; window level: 2,000 HU) showing the first entry wound at the level of the occipital-cervical junction (thin black arrow) and the second, more caudally at the level of the cervicothoracic junction (thick black arrow). Note the severity of the vertebral fractures and rostro-caudal compression of the calvarium to the left of the image. The frontal bone (*) and supraoccipital bone (>) are indicated. (B) External view showing two dorso-ventral projectile entry wounds on the dorsal midline caudal to the blowhole.

was severe comminution of the caudal cervical and cranial thoracic vertebra.

Oedema was apparent in the trachea, bronchus and other areas of the respiratory tract. A markedly hyper-attenuating (~ 3000 HU) focus, indicative of a metallic fragment, was noted in the right lung, likely causing the haemorrhage and pleural effusion in the thorax and close to the pericardium. Additional mild pneumothorax was noted in the right lung. On the left side of the body, pneumothorax and complete lung collapse were observed, consistent with projectile fragments noted to have pierced the pleura. A few metallic fragments were also present throughout the thoracic cavity and adjacent to the ventral aspect of the pericardium.

Lesions noted on the PMCT were consistent with the first shot disrupting the atlanto-occipital and atlanto-axial joints, with metal fragments remaining lodged in the anterior of the right scapula (Figure 3). The second shot, caudal to the first, disrupted the cervical and thoracic vertebrae causing collapse in both areas. The cerebrum appeared undisturbed, but the brainstem was disrupted. These findings were confirmed on dissection, with fractures evident in the caudal aspect of the occipital bone, condyles and cervical vertebrae. Projectile fragments were found within the atlanto-occipital joint and cervical vertebrae, and the caudal brainstem was damaged (Table 3).

Bottlenose dolphin 2

According to the DOC incident report, the bottlenose dolphin was part of a mixed-species mass stranding event, and re-floatation was attempted; however, the animals re-stranded, and the decision was made to euthanise. Two lateral shots were applied using a 30-06 calibre rifle and 140-grain, soft-point projectiles (Table 2). No external exit wound was present on the contralateral side. The marksperson estimated time to death to be between 0 and 30 seconds, stating that "*a big exhale could be heard when you got it just right the first time. Tapping of the eye was used to check if animal was dead*."

From PMCT, the projectile was discharged laterally and caudo-ventrally at the level of the right temporal/parietal bones. On the contralateral side, marked, highly comminuted fractures of the right temporal bone and tympanic bulla were present (Figure 4). The occipital condyles also exhibited highly comminuted fractures, which were more severe on the right. A mildly comminuted fracture was also noted ventral to the head of the right mandible.

Many metallic fragments were present around the right temporal bone, dispersed throughout the bony and soft tissues of the head. The metallic fragments were highly concentrated ventral to the right occipital condyle. There was marked, diffuse soft tissue emphysema and moderate pneumocephalus present, which was worse cranially and slightly to the right side. Notably, the projectile was located adjacent to the calvarium rather than entering the cranium, and the brain remained intact. However, the multiple, highly comminuted fractures of the calvarium, involving the sphenoid bones, right petrous and temporal bones and osseous tentorium, suggested that brain tissues would likely have been extruded (Table 3).

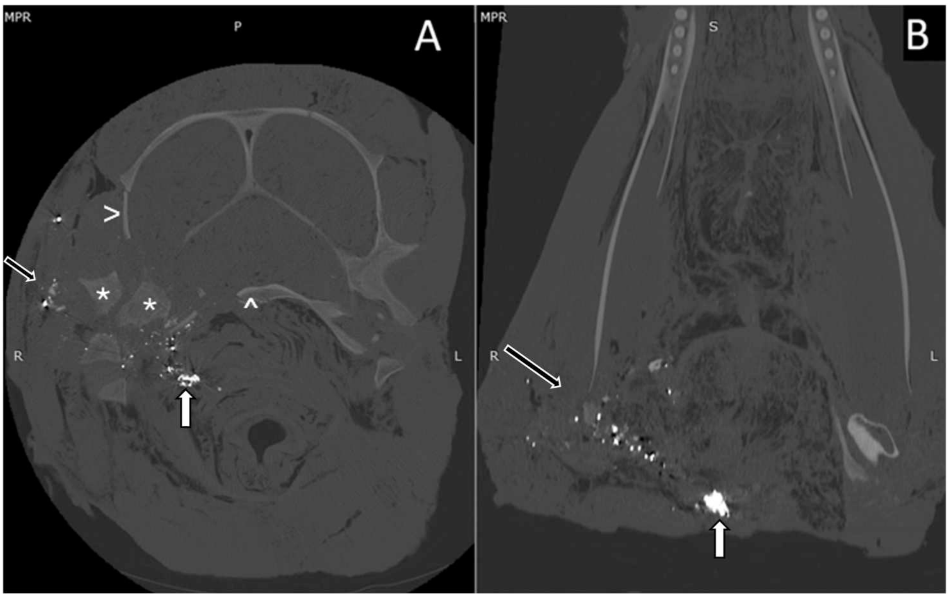

Figure 4. Multiplanar (A) transverse (at the level of tentorium cerebelli) and (B) dorsal reconstruction CT of bottlenose dolphin (*Tursiops truncatus*) 2 in a high-frequency algorithm with an extended CT scale (window width: 9,000 HU; window level: 2,000 HU) showing the initial caudo-ventral entry trajectory at the right lateral aspect of the head (black arrows) and the terminal trajectory of the metal bullet (white arrows). The right parietal bone (>), fractured right occipital bone (*), and basioccipital bone (^) are indicated.

False killer whale

The false killer whale was part of the same mixed-species mass-stranding event as bottlenose dolphin 2, and re-floatation was attempted. Following re-stranding, the decision was made to euthanise; one dorso-ventral shot was applied using a 30-06 calibre rifle and one 140-grain, soft-point projectile (Table 2). The marksperson's comments regarding time to death and assessment of insensibility were as for bottlenose dolphin 2.

The PMCT suggested a mixed dorso-ventral, lateral approach to projectile discharge at the level of the atlanto-occipital joint and in a slightly caudal direction The atlanto-occipital joint appeared widened dorsally. A non-displaced fracture line was present from the left cranio-lateral aspect of the supraoccipital bone with extension to the caudo-dorsal left occipital condyle. Fracture lines were observed along the body of the atlas and multiple fractures were noted within the cranial cervical vertebral bodies.

A moderate number of small metal fragments were present within the atlas and cranial cervical vertebrae. A larger focus of metal attenuation was found lodged within the soft tissues ventral and adjacent right to the displaced cranial cervical vertebrae (Figure 5). Notably, the brain remained undisturbed, although fractures along the left occipital condyle suggest kinetic forces would likely have reached the brainstem (Table 3). The sutures of the calvarium, maxilla and rostrum were prominent, suggestive of a juvenile animal.

Pygmy sperm whale

According to the DOC incident report, the stranded pygmy sperm whale was euthanised based on welfare and survival implications of maternal dependency. One lateral shot was applied using a 30-06 calibre rifle and a 180-grain, solid slug projectile "*parallel with the eye halfway between the front flipper and eye*" (Table 2). No external exit wound was present on the contralateral side. The marksperson estimated time to death to be instant.

A single transverse shot penetrated the left lateral head at the level of the zygomatic process of the temporal bone. There were multiple, highly comminuted fractures across the bullet trajectory involving both temporal bullae, pterygoid bones and multiple, mildly displaced fractures of the basisphenoid and basioccipital bones in proximity to the brainstem, and of the left and right ramus of the mandible. Multiple, small hyperattenuating metallic and bone fragments were observed across the projectile trajectory through the muscle below the base of the calvarium, these include the hyperattenuating fragments of the tympanic bullae. However, no bone or metallic fragments were found within the calvarium. A focal collection of metal fragments was present within the region of the right tympano-periotic complex, close to the expected exit wound (Figure 6). The terminal trajectory of the projectile appeared to be lateral to the right petrous temporal bone (Table 3).

Spiral/concentric emphysematous gas with increased soft tissue attenuation was present within the right frontal soft tissues adjacent to the midline, compatible with high velocity cavitation injury from ballistics. Intraparenchymal gas was noted throughout the brain, likely due to ballistics trauma. Fractures along the open sutures of the supraoccipital and parietal bones were noted to a similar extent bilaterally. These open sutures were indicative of the juvenile age of the animal.

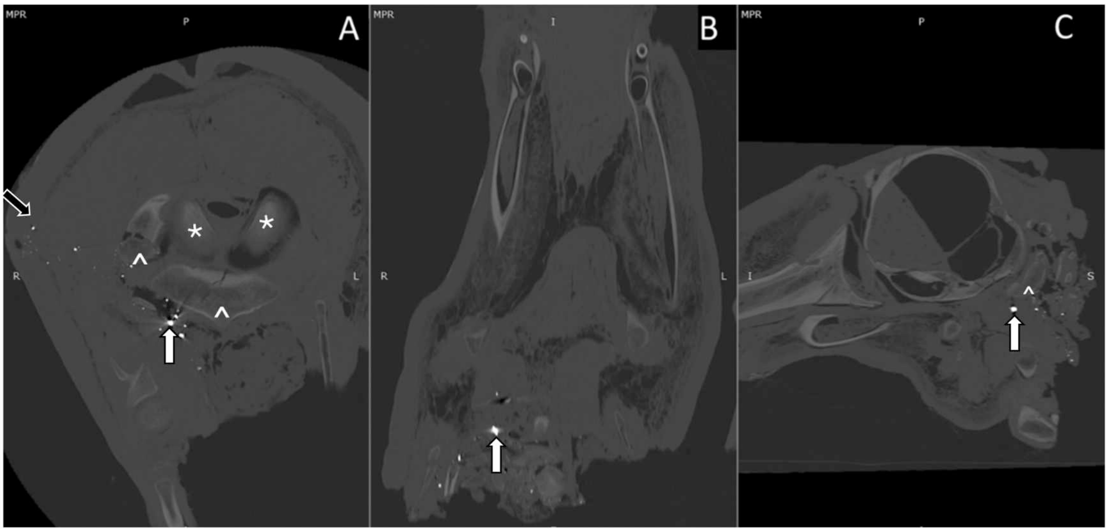

Figure 5. Multiplanar reconstruction CT of a false killer whale (*Pseudorca crassidens*) head in a high-frequency algorithm with an extended CT scale (window width: 9,000 HU; window level: 2,000 HU) centred on the metal bullet (white arrows). The occipital condyles (*) and atlas (C1; ^) are indicated. (A) Transverse plane, with entry trajectory (black arrow); (B) dorsal plane; and (C) para-sagittal plane.

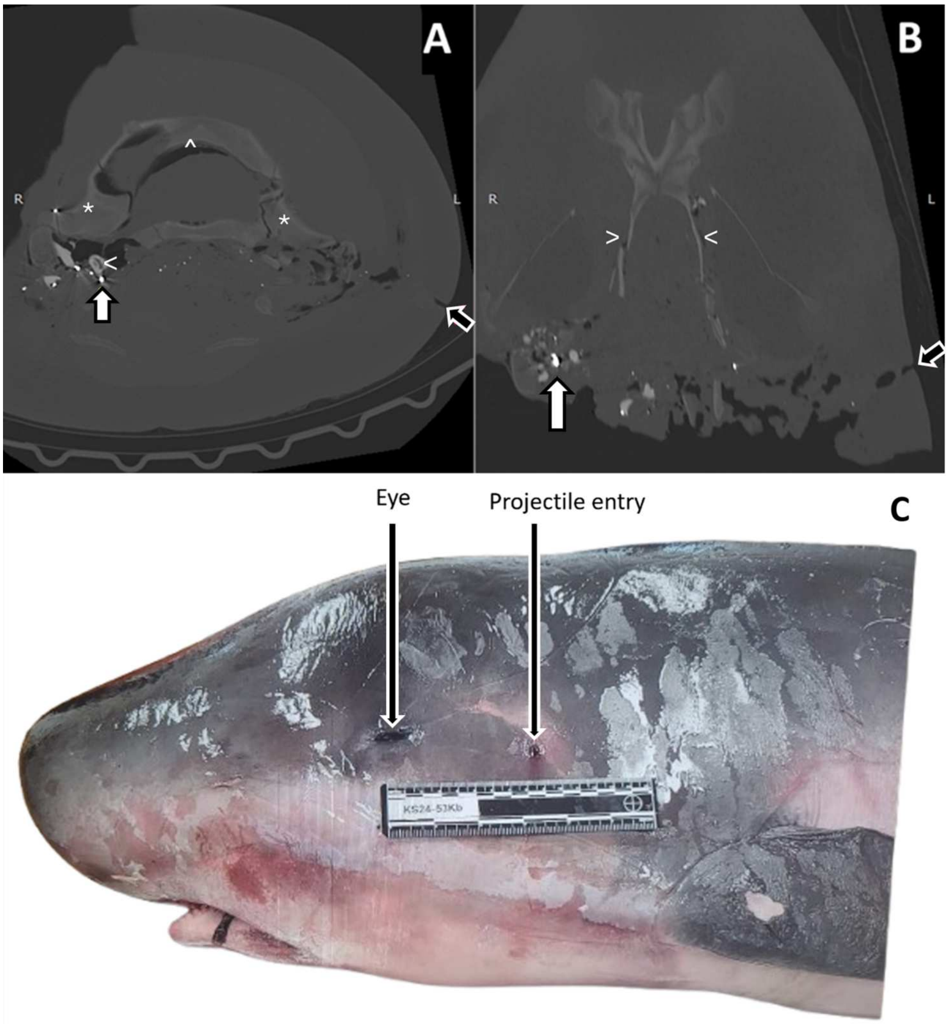

Figure 6. Multiplanar reconstruction CT of a pygmy sperm whale (*Kogia breviceps*) in a high-frequency algorithm with an extended CT scale (window width: 9,000 HU; window level: 2,000 HU). (A) Transverse view of the caudal aspect of the skull with the entry wound (black arrow) and fragments of the metal bullet (white arrow) lodged within the fractured right petrous temporal bone (>). The temporal bones (*) and occipital bone (^) are indicated. (B) Dorsal view with the same entry wound (black arrow) and metal ballistic fragments at the terminal trajectory within the right petrous temporal bone (white arrow). Pterygoid bones are indicated (<). (C) External view of pygmy sperm whale with a lateral projectile entry wound caudal to the left eye.

Likelihood of instantaneous insensibility

Table 3 presents a summary of the likelihood of instantaneous insensibility based on pathophysiology revealed on PMCT and dissection, and the time and signs of insensibility/death reported by the markspersons. Based on PMCT and dissection, two animals were highly likely to have been instantaneously insensible, three had moderate chance of being instantly insensible, and one had a low chance of instantaneous insensibility. In one case, the marksperson's report of time to insensibility/death (TTI/D) was inconsistent with likely insensibility estimates based on PMCT and dissection findings. Specifically, the report suggested that insensibility/death occurred more quickly than it was judged to have occurred from PMCT assessment. Notably, in only two cases were criteria for verifying insensibility reported as being checked ("tapping of eye"). In both cases, the reported TTI/D aligned with the likelihood of instantaneous insensibility based on PMCT findings.

Discussion

Our findings underscore the importance of verifying insensibility through testing of palpebral and corneal reflexes, choosing appropriate projectiles and undertaking accurate shot placement to ensure high welfare standards in field euthanasia praxis. Our conservative estimates suggest that of the six animals assessed in this study, only two (common and dusky dolphin) were highly likely to have been rendered instantly insensible based on pathophysiological findings of brainstem disruption revealed by PMCT and dissection. For these individuals, the marksperson reported TTI/D of 1 second and instant, respectively. One animal (bottlenose dolphin 1) had a low likelihood of instantaneous insensibility, having a completely intact brainstem and no damage to proximal structures. Yet, the marksperson reported that this animal was instantly insensible/dead.

Three other animals (bottlenose dolphin 2, false killer whale and pygmy sperm whale) did not have direct brainstem disruption, but damage to structures in close proximity to the brainstem was observed, providing moderate confidence that shooting caused instantaneous insensibility. In one of these cases (pygmy sperm whale) the marksperson reported TTI/D to be instant with no supporting evidence, whilst for the other two cases TTI/D was reported as 0–30 seconds. These results suggest that marksperson's reported TTI/D were fairly consistent with the likelihood of instantaneous insensibility based on pathophysiological damage revealed by PMCT and at dissection, though the marksperson's methods of verifying insensibility notably did not follow recommendations.

The three animals that did not have direct brainstem disruption had additional unintended lesions outside the cranium. While these animals may have been rendered insensible, the lack of direct brainstem disruption highlights the possibility of further welfare compromise for a short period due to pain from the projectile fragments and disruption of the soft tissues caudal to the cranium and the oesophagus. In contrast, all three maternally dependent cetaceans euthanised via gunshot that were assessed in a previous study, had brain trauma consistent with near-instantaneous insensibility with limited welfare impacts (Boys *et al.* 2024).

Verifying insensibility

Despite the mandate to verify insensibility by testing the palpebral and corneal reflexes in NZ's SOP (Boren 2012; Boys *et al.* 2022), the markspersons apparently did so in only 2/6 (33.3%) cases reported here. In three cases, the markspersons reported death to have occurred based on the absence of movement following shooting. However, use of general movement as an indicator of the presence or absence of sensibility has been found not to be appropriate following ballistics euthanasia in cetaceans, with certain behaviours (e.g. tail fluttering) continuing to occur after insensibility had been confirmed (Boys *et al.* 2024, 2025). Thus, the use of such parameters instead of the recommended reflex testing could lead to under- or over-estimation of the time to irreversible insensibility and duration of any negative welfare impacts following shooting.

It is unknown why there was a lack of appropriate verification of insensibility in more than half of the animals in this study. In a previous study in NZ, at least one marksperson reported not verifying insensibility by corneal/palpebral reflex testing following shooting due to the marksperson being concerned that it was culturally inappropriate when iwi were present (Boys *et al.* 2025). Indeed, the SOP used to guide stranding responses states the requirement for iwi support (among other factors) when considering an appropriate response (Boren 2012). For euthanasia, iwi must be consulted and typically agree prior to implementation, though according to the SOP, the decision to euthanise "*must be made purely for the welfare of the animal involved*." Despite this statement on euthanasia, the SOP also states that animals may be left to die naturally in cases where euthanasia is likely to cause "*significant antagonism between DOC and public/bystanders/iwi*," a situation which has arisen previously (Boys *et al.* 2022). This suggests that human perceptions/sensitivities may sometimes override animal welfare considerations, which could exacerbate welfare impacts (Boys *et al.* 2022; Stockin *et al.* 2022).

High animal welfare standards must be adhered to in wildlife management to ensure both humane outcomes for the animals involved and public support, which will otherwise affect the ability to carry out management practices (Hampton and Teh-White 2019). Agreement on what constitutes acceptable or optimum animal welfare in emergency wildlife management situations, such as re-strandings, will vary depending on people's values (Warburton *et al.* 2008). However, discussion among stakeholders should be undertaken to understand the possible improvements that can be achieved under field conditions.

Selection of equipment and application of ballistics

The aim of shooting is for the projectile to pass its kinetic energy into the tissue to cause significant crushing, stretching and laceration along the trajectory path (Caudell 2013). Therefore, the effectiveness of the shot and resulting animal welfare outcomes are highly dependent on aim, the correct anatomical landmark being targeted and the behaviour of the projectile once it hits the target, to determine the amount or severity of tissue disruption that occurs (Maiden 2009; Hampton *et al.* 2016). The DOC SOP provides guidance to markspersons for the application of cetacean euthanasia including information on the anatomical landmark, angle of aim, and equipment to use (Boys *et al.* 2022).

Shot placement and aim

Of the six cases in this study, two shots were applied dorso-ventrally on the midline using the blowhole as an anatomical landmark, and one was applied dorso-ventrally but to the right side of the head. Three were applied laterally with the eye as an anatomical landmark.

Notably, in three cases the brain itself remained undisturbed, as the shots did not penetrate the calvarium, but this did not depend on approach (two lateral and one dorso-ventral/lateral). For one of the lateral shots (pygmy sperm whale), entry of the projectile was ventral to the recommended eye level and likely deviated due to contact with the bony protrusion of the zygomatic process of the temporal bone. The two others were placed caudal to the recommended location in the chosen plane of aim (Hampton *et al.* 2014; Boys *et al.* 2022).

These findings highlight the need for improved targeting and accuracy of shot aim. In the first instance, markspersons should regularly refamiliarise themselves with recommendations on shot placement and follow such guidance more closely. Further research should also be undertaken to develop species-specific guidance for shot placement based on varying cranial structures among cetacean species (Gol'din 2014; Roston and Roth 2019). We also recommend that markspersons should undergo ongoing training with regular refreshers that cover details such as accurate targeting. While it is difficult to arrange training with cetacean cadavers, the use of theoretical and practical practice via the development of life-like cetacean models (e.g. Thali *et al.* 2002; Dybdal *et al.* 2023) and augmented reality simulators (e.g. De Vreese *et al.* 2023) is encouraged as part of recommended annual training.

In one further case (common dolphin), two shots were placed caudal to the current recommendation for a dorso-ventral midline shot. However, in this case, the first shot resulted in brainstem disruption due to the complete collapse of the atlanto-occipital joint. The common dolphin was also found to have pneumothorax and haemorrhaging within the thorax, as well as probable disruption of major cardiac vessels. Had this damage been caused by the first of two shots, the animal would likely have experienced significant welfare compromise due to both pain and severe respiratory impairment. Fortunately, it was likely instantly insensible due to brainstem disruption from the preceding shot, though the failure of the marksperson to confirm the loss of corneal/palpebral reflexes means time to insensibility cannot be validated.

Shot placement appeared accurate for two animals, based on external anatomical landmarks but this did not necessarily translate into ideal intracranial trauma. The dusky dolphin shot laterally was found to have significant disruption in the brain parenchyma, as well as fractures in the occipital condyles and atlas leading to brainstem damage. In contrast, the dorso-ventral shot to bottlenose dolphin 1 did not disrupt the brainstem nor were fractures present in proximal structures, suggesting that this animal remained conscious and aware. This may have been due in part to the acute angle of aim (~ 90°), which has been suggested to be less accurate than an obtuse angle for targeting of the brainstem in cetaceans (Hampton *et al.* 2014; Boys *et al.* 2024). Overall, our results highlight the importance of ensuring both accurate aim and shot placement to appropriately target the brainstem and minimise potential additional welfare compromise.

Projectile characteristics

In this study, soft deforming projectiles were applied in 5/6 cases. Notably, in only two of these cases (bottlenose dolphin 1 and dusky dolphin) did the projectile enter the cranium to cause damage directly to the brain. In the case of bottlenose dolphin 1, the dorso-ventral shot did not reach the brainstem, and there were fewer osseous lesions outside the projectile trajectory to suggest the creation of a temporary cavitation wound. This is likely because soft deforming projectiles are designed to fragment on impact (Thomson *et al.* 2013). Therefore, in species with thick muscle and bones, such as bottlenose dolphins or medium sized odontocetes, there is high absorption of energy on impact, reducing penetrative ability and diminishing the chances of the projectile reaching and disrupting deep targets such as the brainstem (Blackmore *et al.* 1995; Øen and Knudsen 2007; Hampton *et al.* 2014). In support of this, a previous study conducted on pilot whale (*Globicephala melas*) cadavers reported that soft projectiles rarely penetrated the brain in this species (Olsen and Øen 2006). Despite this, markspersons in NZ have, until very recently, predominantly applied soft projectiles for adults of this and other medium-sized odontocete species (Boys *et al.* 2021, 2023, 2025).

In contrast, the dusky dolphin, which had thinner cranial structures, displayed more extensive skull fractures and disruption to the brainstem with the soft deforming projectile applied. This was likely due to minimal projectile fragmentation and loss of kinetic energy on entry to the skull, allowing for additional internal pathology and a higher chance of rapid insensibility. Similarly, studies involving other small delphinids with thin and/or unfused cranial sutures have found that soft deforming projectiles can cause brainstem disruption and rapid insensibility when applied accurately (Boys *et al.* 2024).

In certain cases, fragmentation may result in insensibility, for example, in the event of inaccurate targeting, a moderately fragmenting projectile that has entered the cranium may increase the likelihood of some disruption to a key structure, such as the brainstem. However, the high fragmentation of soft deforming projectiles also gives rise to the potential for deviation and ricochet which can lead to additional unintended lesions outside the target region (AbdulAzeez *et al.* 2018; Boys *et al.* 2024). Indeed, in this study, projectile fragments were found in the blubber and acoustic fat of the dusky dolphin on the contralateral side from the shot. In animals not rendered instantly insensible, such additional wounding could present significant welfare concerns due to pain and functional impairment caused. Therefore, it is internationally recommended to use solid non-deforming projectiles for cetacean euthanasia (Duignan and Anthony 2000; Øen and Knudsen 2007; Hampton *et al.* 2014).

In only one case (pygmy sperm whale) was a solid, non-deforming projectile used in this study. These projectiles rely on temporary cavitation and hydrostatic shock to disrupt tissues (Maiden 2009) but have improved penetration depth. Accordingly, these projectiles have an increased likelihood of reaching the brainstem in species with thick muscle and bone. A previous study found that a solid, non-deforming projectile caused considerable damage to the brain, brainstem and spinal cord, and was appropriate to euthanise a pygmy sperm whale calf (Boys *et al.* 2024). However, inappropriate aim may result in such solid non-deforming projectiles not reaching the intended target, leading to welfare concerns of wounding rather than insensibility. Indeed, in this study, the single solid projectile applied to the pygmy sperm whale did not enter the calvarium and instead passed ventral to the cranial floor, failing to directly disrupt the brainstem. However, the temporary cavitation from the projectile caused additional pathology (Zhang *et al.* 2005; Øen and Knudsen 2007), fracturing the basisphenoid and basioccipital bones, and producing a moderate likelihood of rapid insensibility. This may only have been possible due to the young age and open cranial sutures of this particular individual, which enabled more disruption proximal to the brainstem than might occur in an older animal of this species.

Overall, these observations indicate the importance of considering species-specific knowledge when choosing ballistics equipment to use for cetacean euthanasia. Cetacean species exhibit unique cranial features, including variable skull morphology (Gol'din 2014; Roston and Roth 2019), cancellous lipid-filled bone, and thick muscle on the skull (Gray *et al.* 2007; Roston and Roth 2019) that can influence projectile trajectory and how it interacts with tissues. In some of the cases examined, there was evidence that cranium penetration was achieved with soft projectiles. However, it cannot be assumed that soft projectiles would sufficiently penetrate the larger muscle mass and thicker craniums of other cetacean species to reach the targeted brainstem, and/or that sufficient kinetic energy would remain in fragmented soft projectiles to cause temporary cavitation. Therefore, it is vital that appropriate projectiles are used for the species and size/age of the individual being euthanised, to reduce the chances of non-fatal wounding and delayed insensibility, which would lead to significant welfare compromise (Hampton *et al.* 2021).

The paucity of standardised studies examining the effectiveness and humaneness of firearms in wildlife management settings (e.g. Hampton *et al.* 2014) means that only limited robust information is available. Methods can be refined by collecting animal-based data, such as frequency of non-fatal wounding and time to insensibility, to infer welfare impacts. Such information, as collected in this study, would be highly beneficial to decision-makers (Caudell *et al.* 2009) and ensure the best animal welfare outcomes in emergency wildlife management.

Methods for evaluating ballistics euthanasia

To the best of our knowledge, this is only the second study to use PMCT to evaluate ballistics euthanasia applied to stranded cetaceans (Boys *et al.* 2024). Since PMCT and dissection post-ballistics cannot be used to assess damage to neuronal tissue, we conservatively defined the likelihood of instantaneous insensibility based on direct disruption to the brainstem, which has a vital role in conscious awareness (Parvizi and Damasio 2003; Taran *et al.* 2023) and functioning of the cardio-respiratory systems (Cozzi *et al.* 2016; Panneton and Gan 2020). In the three cases where we were able to undertake dissection of the head following PMCT, we found gross evidence corroborating PMCT findings, suggesting that such imaging can be used to robustly evaluate cranial damage following ballistics. However, more detailed dissection and histopathology should be undertaken alongside other imaging modalities (e.g. magnetic resonance) and angiography to further evaluate specific brain regions disrupted by ballistics, as has been conducted in humans (Oehmichen *et al.* 2003; Thali *et al.* 2003). Notably, PMCT provides an effective non-destructive method of validating markspersons' field evaluations of TTI/D, enabling robust scientific assessments.

Conclusion

This study contributes important empirical data to the limited evidence base to better inform the use of ballistics for the humane killing of debilitated stranded cetaceans. The case studies presented here provide insight into key aspects which must be considered to ensure effective euthanasia, including species-specific differences, shot placement, projectile type and verification of insensibility. Understanding differences in cranial structure of each species and bone density can improve decisions about equipment selected for ballistics euthanasia and reduce the risk of non-lethal injuries that prolong suffering. These insights are essential for refining euthanasia protocols to ensure the best possible animal welfare outcomes at stranding events.

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