

CRANIAL TRAUMA IN BEAKED WHALES

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INTRODUCTION Beaked whales (Ziphiidae) are a ubiquitous but poorly understood group of marine mammals. Our knowledge of them has been limited largely to off-shore sightings, surface observations, and gross measurements, often from poorly preserved animals. Historically, they are more frequently found as single stranded animals and most species rarely mass strand. For a very few species, well-preserved material is available but much of it has not been dissected nor employed in experimental work because of the rarity of specimens. Playback experiments in free-ranging animals have also been difficult to achieve, and there is to date no published, clearly verified vocalisation data for any beaked whale species (Wartzok and Ketten, 1999). We therefore know relatively little about ziphiid behaviour or physiology in general, and virtually nothing of their use of sound or hearing abilities.

Recent mass strandings of beaked whales in Greece, the Bahama Islands, Madeira, and the Canary Islands suggest that beaked whales - and particularly Cuvier's beaked whale (*Ziphius cavirostris*), are prone to stranding following exposure to high intensity impulse noise, particularly mid-frequency sonar. Beaked whale mass strandings are notable because, unlike pilot whales and white-sided dolphins, these animals do not live in large social groups and do not commonly mass strand. One of the difficulties of reviewing stranding statistics on beaked whales historically is that species identification is difficult. Cuvier's beaked whales have been reported to mass strand more frequently than other beaked whale species, but they are relatively rare world wide, and only two prior mass stranding events of beaked whales have been reported for the Bahamas in the last 150 years.

Each of the above noted strandings coincided with a U.S. Navy, NATO/SACLANT, or European naval exercise that involved ships utilising tactical mid-frequency sonars. These events have generated considerable concern that sonars instigated the strandings and may have directly or indirectly caused the deaths and traumas found in the beached whales. Clearly, there is an acute need to understand whether sonar was a direct or indirect agent in the injuries to these whales, the precise mechanism behind the traumas that were found, and the nature and extent of potential impacts from man made sounds, particularly from sonar and impulse noise, on these elusive animals.

To that end, organised retrospective investigations are being conducted for each of these strandings. Full details of the Bahamian stranding and results of subsequent related studies may be obtained from the report on this event available at the following website:

www.nmfs.noaa.gov/prot_res/overview/Interim_Bahamas_Report.pdf

This paper summarises the stranding and results from the radiological examinations and necropsies of the whales that died in the Bahamian stranding event of March, 2000, and discusses the potential mechanisms of traumas based on the pathologies observed. Multiple researchers and pathologists

are involved in determining the findings in these cases. The final consensus report is in preparation and the data presented here is not to be considered binding or final. The findings reported in this paper represent primarily the findings by the senior author at this time and should not be construed to represent views of NOAA Fisheries or any other investigator. Final conclusions will be released by NOAA Fisheries in the report expected in spring 2004.

BAHAMIAN STRANDING EVENT SUMMARY On 15 and 16 March 2000, 17 cetaceans were reported stranded along a 240 km arc in the Northeast and Northwest Providence Channels of the Bahamas Islands. The strandings, with the exception of one animal, were spread along the western shores of three islands (Grand Bahama, Abaco, and North Eleuthera) and comprised four species distributed as follows: ten Cuvier's beaked whales (*Ziphius cavirostris*), three Blainville's beaked whales (*Mesoplodon densirostris*), two unidentified beaked whales, one spotted dolphin (*Stenella frontalis*), and two minke whales (*Balaenoptera acutorostrata*). Seven of these animals died, including five Cuvier's beaked whales, one Blainville's beaked whale, and one spotted dolphin. The remaining ten live animals were successfully pushed into deeper water or swam away and did not restrand, however, the longer term fate of these animals is unknown at this time. Based on the condition and location of each of the stranded animals in this event, it is likely that all animals stranded within a narrow time frame on the morning of 15 March. Strandings were first noted at the southern end of the channels and reports proceeded northwest throughout the following 36 hours. The spotted dolphin and minke whales stranded in areas well separated from the beaked whales. Both minke whales came to shore alive and returned to deeper water on their own. Because these two animals were not examined in any way, no definitive statements can be made about the cause of their stranding or whether they sustained any subtle injuries in common with the beaked whales.

SHIP MOVEMENTS AND ACOUSTIC MODELLING

Commander in Chief of the U.S. Atlantic Fleet prepared a report (Evans and England, 2001) which described in detail the timing and courses of U.S. Navy ships in the Northeast and Northwest Providence Channels on March 15, 2000. Numerous ships transited from the southeast to the northwest in generally the same pattern as the strandings were discovered. Five ships used their main frame active sonar in the channels during the time of interest. Two ships operated the tactical mid-frequency sonar designated AN/SQS-53C and two operated sonar designated AN/SQS-56. During the 16-hour period in which the ships transited the channel using sonar, each ship pinged its sonar approximately every 24 seconds with pings from nearby ships staggered in time so as not to coincide. Because the ships did not operate at the same frequencies, and because the ships with the same frequency sonars did not operate in the same temporal and spatial proximity, there is little likelihood of increased sound pressure levels from multiple simultaneous pings.

GROSS NECROPSY RESULTS The post-mortem condition of the seven animals that died ranged from fresh dead to advanced decomposition. Six of the seven mortalities were necropsied to the fullest extent possible. Only three of these animals, one Cuvier's beaked whale, one Blainville's beaked whale, and the spotted dolphin, were sufficiently fresh to provide gross and histo-pathology results for most of the available tissues (albeit there was post-mortem autolysis noted in all of the beaked whale tissues).

The spotted dolphin was the only animal stranding on the eastern shore of the islands. The necropsy of this animal revealed chronic, systemic, debilitating disease in multiple organ systems.

It did not have any of the trauma elements found in the beaked whales that died. Based on the location of the animal and the clear evidence of long term disease typical of many stranded animals, it was concluded that the spotted dolphin in this event was a coincidental stranding and its beaching was unrelated to the mass stranding event of the beaked whales that same day.

The remaining six animals that died were all Cuvier's and Blainville's beaked whales. One was severely decomposed and was only partially necropsied. The other five were fully necropsied, and heads of two of the animals were examined radiologically. All five animals examined were in good body condition, and none showed evidence of debilitating infectious disease, ship strike, blunt contact trauma, or fisheries related injuries. Three of the beaked whales had small amounts of ingesta in the stomach. Similar to findings in many stranded cetaceans, distinct band lesions - consistent with stress, were found in histological examinations of the heart muscle. Similar common stranding-related lesions were found in the spleen, liver, and kidney. These pathologies are consistent with death from cardiovascular collapse due to extreme physiologic stress associated with the physical stranding; *i.e.*, hyperthermia, high endogenous catecholamine release, and shock.

CRANIAL NECROPSY RESULTS Whole heads and ears obtained as post-mortem specimens from the strandings listed above were examined first by computerised tomography (CT scanning) to assess tissue conditions and gross pathology of the head and particularly of the brain and peripheral auditory system. Measurements of pathological blood deposits and three-dimensional reconstructions of the heads and ears were obtained from the scan data and images. Four ears from two animals were re-examined after extraction of the ear complex by ultra-high resolution, 100 micron section CT scan imaging and light microscopy. These results were compared with data from single stranded animals of the same species that were collected under the NMFS stranding response efforts in the United States from 2000-03. The chief objective of the study was to determine the nature and extent of the physiological impacts these animals sustained, and to determine whether impacts in the presence of sonar are different than those found in other stranded animals.

The scan and necropsy analyses of single stranded animals show that beaked whales have ear structures in common with most odontocetes, but some significant differences were found in ear and airway anatomy compared with other marine mammals.

General beaked whale scans reveal an exceptional ear anatomy (Ketten, 1998). Beaked whales have a fundamentally odontoid temporal bone, but there is an auxiliary bony element at the Eustachian tube aperture (Fig. 1). This sesamoid shaped bone has a flexible synostotic joint. It attaches to the tube and appears to act as a strut to prevent closure. The periotic is also partly fixed to the squamosal, like that of the physeterids but less substantially than in mysticetes. The inner ear is classically odontoid with one notable exception: the vestibular divisions are remarkably well developed. The vestibule is large and bulbous, and the vestibular nerve trunks appear to represent well over the conventional 5% of the VIIIth nerve common in other cetaceans. Hearing ranges vary with each species; however, all beaked whales have conventional odontocete adaptations for good ultrasonic hearing. The lower frequency capacity is heavily species dependent. Ganglion counts are considered incomplete at this time, as the majority of specimens have spotty losses coincident with trauma and age induced hearing loss.

CASE RESULTS: BAHAMIAN STRANDED BEAKED WHALE STUDIES

Ears and intact heads were examined from the animals noted above that were considered to be in adequately fresh condition to warrant full analyses. The heads were examined by 0.1 to 3 mm section CT imaging as described and by gross necropsy. Ears from some additional animals were scanned also after extraction. To date, six of the extracted ears have been scanned, histologically processed, and examined.

In no animal was there evidence of profound or near-field blast damage, but in all three of the fresher heads, there is evidence of *in vivo* cranial trauma. This evidence consisted of intra-cochlear (IC) and temporal region subarachnoid haemorrhages (SAH) with lateral ventricular clots (LVH). In simpler terms, there are deposits of blood within some of the inner ear chambers and in at least two animals, there was haemorrhaging in a discrete region of the fluid spaces surrounding the brain (Fig. 1). These pathologies were first observed in the CT scans and subsequently confirmed by gross dissection.



Fig. 1. Left: A 2D CT scan 3 mm slice transaxial image at the temporal lobe level of a Blainville's beaked whale. The arrow and circle indicate a subarachnoid haemorrhage in this region. Fresh blood is also visible in the internal auditory canal. The head was partially flensed during the original field dissection, hence the lack of soft tissue on the dorsal surface of the head. Right: A 3D reconstruction demonstrates the distribution of blood (red) in the fluid space around the brain (pink), and its path along the internal auditory canal leading to the ear bones (white) and the jaw fats (yellow).

CONCLUSIONS The number and coincidence of the strandings combined with these necropsy findings, and with the fact that these strandings appear to be dominated or exclusively beaked whales, suggest a species dependent related trauma. The patchy patterning of blood in the *Ziphius* and *Mesoplodon* ears indicates that the inner ear membranous partitions and major nerves were intact and that the internal auditory canal and cochlear aqueduct were conduits for blood movement between the cranial and inner ear spaces. The presence of blood in only restricted intracranial spaces and the intact inner ear membranes are not consistent with simple post-mortem pooling. Indiscriminate post-mortem pooling is generally greater on the side down on beaching, and occurs throughout the whole ear because normal ear tissues that divide the inner ear are lost through post-mortem necrosis, and blood collects preferentially in dependent areas. The patterning of the haemorrhages therefore suggests the ear was structurally intact and the animals were alive at the time of injury.

Findings in the poorly preserved specimens are consistent with those in the fresher animals, but are not strong data nor conclusive, because of the animals' poor condition. Observations are consistent for all animals examined to the extent that bloody effusions were found in and near the ears, and there were no indications of ship strike or other large, direct impacts. However, in the three poorest specimens, we cannot rule out post-mortem migration and deposition of blood in the auditory areas.

There are several important implications from these observations. First, the level of intracochlear blood and haemorrhage in these animals is consistent with a transient, intense event. Second, the observed damage does not necessarily indicate permanent hearing loss or acute, direct mortality. While similar lesions in humans can be painful, humans with similar auditory system haemorrhage and animals with similar experimentally induced lesions in lab studies typically regain hearing that may be impaired by the event (hearing loss is transient). In some cases there is often no significant hearing loss reported at all.

The actual observed cause of death in these animals was the physical consequences of stranding, including hyperthermia, suffocation, cardiovascular collapse, shock, and blood loss from external wounds from coral cuts, shark attack, etc. Therefore, the cause of the cranial trauma *per se* was not immediately lethal in these animals, but it may be an important contributory, or even the causal, factor for the strandings. Even if the auditory damage evident in the necropsied animals were recuperable in terrestrial animals, it is still important to analyse it carefully, to determine its cause, and to identify potential mitigation measures since it is likely to have played a significant role, perhaps by initiating the strandings.

Based on current medical and experimental data, the haemorrhagic patterns observed in these animals are found in the following etiologies in other mammals (*n.b.*: order not significant): concussive acoustic trauma from blasts or intense impulse events, barotrauma, direct or contact concussive trauma (head blows with or without fracture), auditory concussion from non-impulse source, sonic booms, spontaneous subarachnoid haemorrhage and hyperemia (bleeding into the cranial fluid spaces), vestibular atelectasis (vestibular collapse accompanied by sudden vertigo and nausea), intraoperative birth trauma (canal squeeze and forceps use), and diathetic (haemorrhage enhancing) disease.

There was no evidence or reports of explosions or underwater blasts in the vicinity or near the time of these strandings. Direct or concussive trauma can be ruled out because there were no surface marks, fractures, or contusions that would accompany blunt trauma. The number, temporal coincidence, and age of the animals stranding make birth trauma and random spontaneous haemorrhage unlikely candidates for a cause. Diathetic disease? In humans, diseases related to subarachnoid and intracochlear haemorrhages include several diseases or conditions; e.g., haemophilia (rarely), Wegener's granulomatosis, and leukaemia. Were any of these diseases present, there should be confirming evidence in the body tissue histological analyses. It is also possible that beaked whales have some diathetic condition that is for them a normal state but makes them particularly fragile to impulse traumas. As with the disease case, looking for symptoms of such a condition should certainly be a priority in the necropsy analyses for beaked whales in this, and in other, stranding cases. Vestibular? A hyper-responsive vestibular system, particularly for lower frequency signals, is certainly an important possibility for beaked whales, considering that they have a better developed vestibular system and Eustachian tube than most cetaceans. Lastly, of course, intense impulsive sources, shock waves, and sources that mimic pressure characteristics of sonic booms are possible and clearly warrant careful consideration. It is important to note, however, that the traumas described do not constitute classic acoustic trauma which would involve

sudden and definitive damage to the cochlear duct components of the inner ear and possibly to the middle ear tissues, the ossicles, and the tympanic membrane

In summary, the findings in the beaked whale heads examined to date are that haemorrhages were found in the inner ears and some cranial spaces. These pathologies are consistent with trauma that may have compromised hearing but was not immediately lethal. Other related observations include haemorrhages and contusions in the jaw fats and mandibles in some of the animals. The pattern of damage is consistent with several causes, including indirect acoustic effects, diathetic fragility, vestibular sensitivity, and behavioural responses. None of these can be ruled out at this point, and it should be borne in mind that all may represent a contributory element.

Because the strandings coincided both temporally and geographically with a large scale naval exercise involving tactical mid-range frequency sonar, coupled with the nature of the physiological impacts found in the dead animals, and given the absence of any other exceptional or intense acoustic events, the investigation team concluded that the sound field created by the combination of ocean state, topography, and the use of multiple tactical mid-range frequency sonars during the exercise, was an important factor in the stranding event.

The sonars were employed in a complex environment that included the presence of a strong surface duct, unusual underwater bathymetry, intensive use of multiple sonar units, a constricted channel with limited egress, and the presence of beaked whales that appear to be particularly sensitive to the disturbance to the normal environment that the exercise produced. The investigation concluded that the cause of this stranding event was the synergism of these factors. It is not yet clear if any one element, such as frequency, intensity, or the anomalously robust sound field stretching over tens of kilometres, or all, were critical factors. Combinations of factors different from this set may be more or less likely to precipitate strandings. We do know that similar strandings in other areas that involve beaked whales and military activity, have some features in common, but a careful comparative physical analysis is not yet available. To date, there have not been any strandings linked to single mid-range sonar use nor to low frequency sonars. Therefore it is critical that all parameters for which we have data, including the environmental as well as the physiology and pathology results, be examined carefully and in concert, to accurately determine the mechanisms behind this event.

FUTURE RESEARCH The short-term goals of this project were completed; however, it raised several issues that warrant further investigation, particularly hearing range, sound reception, and tissue resonance modelling. More comprehensive light and electron microscopy data on the ears of these species would allow us to determine their hearing ranges and to analyse the sub-structure and conformation of vestibular, middle, and inner ear complexes. Equally important, the availability of whole heads in several museum collections, coupled with scanning analyses, would provide the necessary measurements to determine cranial and Eustachian tube resonances. Given the most recent developments in imaging and segmentation, it is now feasible to consider whole head FEM analyses that would provide high confidence functional simulations of specific frequency range responses in these animals, that are likely to be the keys to acoustic effects observed to date.

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