Sonar versus Whales: Noise may disrupt neural activity in deep-diving cetaceans.

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INTRODUCTION

In humans, and other terrestrial animals, acoustic and non-acoustic detrimental effects of noise have been described long ago (1,2). In the recent years there is an increase in public and expert interest in the potential damaging consequences of acoustic pollution to marine life. The general increase in underwater noise and the use of sonar (1,2) have been associated with behavioral (3, 4) and pathological changes (5) in diving mammalians exposed to such an environment. Among these last, the connection established between the use of high-intensity sonar and the stranding and acute death of whales (6,) is particularly striking. It has been suggested that sonar activity per se may induce either bubble formation similar to decompression sickness (DCS (7)), or direct tissue disruption in diving mammalians (8,9). This may be true at the proximity of high intensity sonars (10,11). But the general signs of DCS observed in stranded cetaceans that were presumably exposed to the mid-range sonar activity at distance (5) suggest a behavioral cause: an accelerated ascent from deep water after being affected by the sonar. We postulate here novel auditory and sensorineural mechanisms by which sonar, and intense noise, may disrupt the behavior of diving cetaceans. Together with this, we also propose that the effects of noise at frequency may be enhanced during deep diving due to a synergistic combination with the adaptive response of the central nervous system (CNS) at high pressure.

Auditory Effects of High Intensity Sound

Dolphins and whales are able to perceive sound beyond the human hearing range. Many species use sounds for behavioral functions like mating (2), echolocation of prey (12,13,14) and orientation during diving (15,16). The echolocation system of cetaceans (mostly demonstrated in odontocetes), in contrast with that of bats, lacks of automatic gain-control on the receiver (ear). So, to compensate for propagation loss, or to protect the ear, cetaceans have to automatically adjust the emission (their output vocal click signal) as they approach the target (17). Because of this feature, the damage inflicted by intense noise to the ears may result in a severe auditory threshold shift (18) and may lead to permanent or transient hearing-impairment. Thus, disabling the echolocation system of the cetacean. If this happens during a deep dive, failure of echolocation may lead to disorientation, speeding up ascent from the depth, and ultimately DCS. Such sensitivity of the ear turns the cetaceans prone to the acoustic assault. This may explain why whales and dolphins can be more susceptible to sonar stimuli (13) than young elephant seals (19). A sensitive auditory system may be the direct target of intense noise (13), but it may also be the trigger of secondary effects (5).

Non-auditory Effects of High Intensity Sound

Whales and other deep-diving mammals perform breath-hold diving with pre-dive expiration, which is followed by lung collapse and redistribution of blood flow. This procedure impedes any gas exchange in the lungs (20). Piantadosi and Thalmann (8) argued that this diving response is enough to avoid DCS under normal conditions. However, if brain function is affected (see Startle response below), the autonomic nervous system may as well be dysfunctional, impairing the preventive maneuvers that impede gas diffusion during the dive response (redistribution of pulmonary blood flow). Thus, a static diffusion of nitrogen in supersaturated tissues, usually affected by repetitive dives, is a possible mechanism for vascular bubbles formation. The crucial question is why whales should react so abnormally, changing their diving or decompression profile in presence of the sonar signal? Even at low pressures high intensity underwater noise was shown to disturb human behavior (21). Non-auditory effects of noise in humans involve annoyance (22), disruption of short-term memory acquisition and maintenance of ordered information (23,24), disturbed auditory verbal processing, and diminished attentional control (25). Startle is a motor and also an autonomic reaction to a totally unanticipated and potentially frightening stimulus. A sudden noise may develop a normal startle response, but a high intensity noise may elicit severe fear or a panic response (26). This kind of response, involving an autonomic component, may disrupt the regular diving response of the cetacean. Furthermore, certain auditory stimuli, such as noise (27) or music (28,29), may eventually provoke epileptic seizures in susceptible subjects.

Effects of high intensity noise may be enhanced at high pressure because of CNS adaptive mechanisms

Humans and experimental animals exposed to high pressure suffer the high pressure nervous syndrome (HPNS), which is characterized by hyperexcitability of the CNS. HPNS often begins with tremor and cognitive disturbance, but also involves autonomic reactions like nausea, vertigo, vomiting and dizziness, and may, in extreme cases, induce epilepsy-like seizures (30). The normal inhibition the respiratory drive by trigeminal and vagal nerves stimulation was reduced, or even reversed to stimulation, under hyperbaric conditions (31).

Development of HPNS has also been associated with unusual discomfort and abnormal psychological symptoms when subjects were exposed to the clicks of an auditory evoked potential (AEP) test (32). Generation of late AEP waves is associated with activation of high-level areas in the cerebrum. Corticohippocampal areas have been shown to participate in these phases of the AEP (33). Some of these high-level areas, are which when abnormally activated by noise at atmospheric conditions, produce the non-auditory deleterious effects of noise. Reduction of synaptic transmission, diminished action potentials conduction velocity and paradoxical hyperexcitability (34,35) are well-known phenomena in the CNS under hyperbaric conditions. Humans, and deep-diving animals may cope with these effects due to certain adaptability of the CNS at high pressure. This adaptation is which presumably allows them to perform and carry out relatively normal tasks at great depths. Our recent experiments in isolated rat brain-slices revealed at a cellular level that this adaptation to high-pressure involves counterbalance of high-pressure-induced synaptic depression by increased dendritic excitability and conduction (36). But this adjustment is not devoid of secondary effects: stimulation of large number of cortical inputs at certain frequencies may boost the activity patterns in neural circuits, and even promote seizure development (38). By this mechanism the repetitive high-intensity noise produced by the sonar pinging may activate more fibers under high-pressure conditions than on surface. Massive activation of corticohippocampal areas will induce corresponding cognitive and autonomic secondary responses that may impair orientation, or maintenance of the regular diving response of the cetacean. Moreover, deep-diving whales seem to be the most affected by sonars (7): the phenomenon of massive stranding is almost exclusive of odontocetes that use echolocation for foraging at great depths. Within this group, the Cuvier's beaked whales are the most likely to be found massively stranded. These whales are also the deepest divers of the group, using to submerge for more than 20 min at depths of approximately 2000 m (37). Other beaked whales found stranded after sonar use, such as Blainville's and Gervais, are also deep divers. Sperm whales, which have the deep-diving world record, occasionally strand, and display signs of DCS in their bones (38). Presence of a huge mass of undigested squid in the stomach of beaked Cuvier whales stranded in the Canary Islands (5) suggest that these animals were severely disturbed by the sonar short after ingesting their meal at great depth (39). Therefore, it is in our opinion, reasonable to assume that in this case whales dead by DCS due to rapid ascent from the depth and/or dysfunction of their physiologic diving response.

CONCLUSIONS

Intense noise affects animals at various levels. Direct effects of noise on matter and animal tissue are expected only in the proximity of high intensity active sonars (mostly low frequency sonars). The auditory effects of intense noise may be particularly harmful for deep-diving cetaceans because of lack of gain-control in their ears. This feature may lead to permanent or transient ear damage together with secondary loss of the echolocation function. Lack of echolocation may be crucial for orientation, in particular when the animal is diving at great depths. Non-acoustic effects of noise may give rise to an enhanced startle response leading to disturbance in the normal behavior. A severe startle response, possibly involving fear or panic, may cause stranding as a flight response. The cumulative effects of high-intensity noise with CNS adaptation to high-pressure seem to play a relevant role in the association sonar use with stranding/DCS in whales. Thus, it is possible that strong noise or sonar signals are more prone to abnormally activate brain areas when animals are concomitantly exposed to high pressure at the depth of the ocean. We propose that these phenomena may interfere with their orientation cues, and alter behavioral traits. In extreme cases, this could cause the stranding of whales. Therefore, it is necessary to encourage the study of neural effects of sound waves on diving mammals under various ambient pressures conditions.

REFERENCES

1. Malakoff D. Ecology. A roaring debate over ocean noise. *Science* 2001; 291:576-8.
2. Malakoff D. Seismology. Suit ties whale deaths to research cruise. *Science* 2002; 298:722-3.
3. Miller PJ, Biassoni N, Samuels A, Tyack PL. Whale songs lengthen in response to sonar. Nature 2000; 405:903.
4. Foote AD, Osborne RW, Hoelzel AR. Environment: whale-call response to masking boat noise. *Nature* 2004; 428:910.
5. Jepson PD, Arbelo M, Deaville R, et al. Gas-bubble lesions in stranded cetaceans. *Nature* 2003; 425:575-6.
6. Dalton R. Scientists split over regulations on sonar use. *Nature* 2003; 425:549.
7. Piantadosi CA, Thalmann ED. Pathology: whales, sonar and decompression sickness. *Nature* 2004; 428:1.
8. Schrope M. Whale deaths caused by US Navy's sonar. *Nature* 2002; 415:106.
9. U S Dept Commerce & US Navy Joint Interim Report: Bahamas Marine Mammal Stranding Event of 15-16 March 2000. http://www.nmfs.noaa.gov/prot_res/overview/Interim_Bahamas_Report.pdf
10. Schrope M. Sonar system offered special dispensation. *Nature* 2001; 410:505.
11. Rehn KW, Riggs PK. Non-lethal swimmer neutralization study. Applied Research Laboratories, The University of Texas at Austin 2002; http://www.spawar.navy.mil/sti/publications/pubs/td/3138/td3138cond.pdf
12. Harley HE, Putman EA, Roitblat HL. Bottlenose dolphins perceive object features through echolocation. *Nature* 2003; 424:667-9.
13. Philips JD, Nachtigall PE, Au WW, Pawloski JL, Roitblat HL. Echolocation in the Risso's dolphin, Grampus griseus. *J Acoust Soc Am* 2003; 113: 605-16.
14. Madsen PT, Kerr I, Payne R. Echolocation clicks of two free-ranging, oceanic delphinids with different food preferences: false killer whales Pseudorca crassidens and Risso's dolphins Grampus griseus. *J Exp Biol* 2004; 207:1811-23.
15. Thode A, Mellinger DK, Stienessen S, Martinez A, Mullin K. Depth-dependent acoustic features of diving sperm whales (Physeter macrocephalus) in the Gulf of Mexico. *J Acoust Soc Am* 2002; 112:308-21.
16. Miller PJ, Johnson MP, Tyack PL. Sperm whale behaviour indicates the use of echolocation click buzzes "creaks" in prey capture. *Proc R Soc Lond B Biol Sci* 2004; 271:2239-47.
17. Au WW, Benoit-Bird KJ. Automatic gain control in the echolocation system of dolphins. *Nature* 2003; 423:861-3.
18. John E. K. Foreman, Sound Analysis and Noise Control. Van Nostrand Reinhold, New York. 1990.
19 Costa DP, Crocker DE, Gedamke J, et al. The effect of a low-frequency sound source (acoustic thermometry of the ocean climate) on the diving behavior of juvenile northern elephant seals, Mirounga angustirostris. *J Acoust Soc Am* 2003; 113:1155-65.
20. Williams TM, Davis RW, Fuiman LA, et al. Sink or swim: strategies for cost-efficient diving by marine mammals. *Science* 2000; 288:133-6.
21. Steevens CC, Russell KL, Knafelc ME, Smith PF, Hopkins EW, Clark JB. Noise-induced neurologic disturbances in divers exposed to intense water-borne sound: two case reports. *Undersea Hyperb Med* 1999; 26:261-5.
22. Shepherd M. Pollution, noise, and mental health. *Lancet* 1975; 1:322-4.
23. Hughes R, Jones DM. The intrusiveness of sound: Laboratory findings and their implications for noise abatement. *Noise Health* 2001; 4:51-70.
24. Nicholls AP, Jones DM. The sandwich effect reassessed: effects of streaming, distraction, and modality.*Mem Cognit* 2002; 30:81-8.
25. Kujala T, Shtyrov Y, Winkler I, Saher M, Tervaniemi M, Sallinen M, Teder-Salejarvi W, Alho K, Reinikainen K, Naatanen R. Long-term exposure to noise impairs cortical sound processing and attention control. *Psychophysiology* 2004; 41:875-81.
26. Spreng M. Central nervous system activation by noise. *Noise Health* 2000; 2:49-58.
27. Manford MR, Fish DR, Shorvon SD. Startle provoked epileptic seizures:features in 19 patients. *J Neurol Neurosurg Psychiatry* 1996; 61:151-6.
28. Avanzini G. Musicogenic seizures. *Ann N Y Acad Sci* 2003; 999:95-102.
29. Wieser HG. Music and the brain. Lessons from brain diseases and some reflections on the "emotional" brain. *Ann N Y Acad Sci* 2003; 999:76-94.

30. Bennett PB, Rostain JC. “The High Pressure Nervous Syndrome” in Bennett and Elliot’s Physiology and Medicine of Diving (eds Brubakk, A.O. & Neumann, T.S.) 5th edn 323 (Saunders, Philadelphia, (2003).
31. Tarasiuk A, Grossman Y. High pressure modifies respiratory activity in isolated rat brain stem-spinal cord. *J Appl Physiol* 1991; 71:537-45.
32. Weibing X, Qingling Z, Lingsong P, Ruqing T. Changes in human brainstem auditory evoked potentials during a 1,100 kPa He-O2 simulated saturation dive. *Undersea Hyperb Med* 1998; 25:111-4.
33. Foster TC, Deadwyler SA. Acetylcholine modulates averaged sensory evoked responses and perforant path evoked field potentials in the rat dentate gyrus. *Brain Res* 1992; 587:95-101.
34. S. Daniels, Y. Grossman, in Bennett and Elliot’s Physiology and Medicine of Diving (eds Brubakk, A. O. & Neumann, T.S.) 5th edn 265 (Saunders, Philadelphia, 2003).
35. Talpalar AE, Grossman Y. Modulation of rat corticohippocampal synaptic activity by high pressure and extracellular calcium: single and frequency responses. *J Neurophysiol* 2003; 90:2106-14.
36. Talpalar AE, Grossman Y. Enhanced excitability compensates for high-pressure-induced depression of cortical inputs to the hippocampus. *J Neurophysiol* 2004; 92:3309-19.
37. Baird RW, McSweeney DJ, Ligon AD, Webster DL. Tagging feasability and diving of Cuvier’s beaked Whales (Ziphius cavirostris) and Blainville’s beaked whales (Mesoplodon densirostris) in Hawaii. http://www.dal.ca/~whitelab/rwb/BairdetalHawaiibeakedwhales2004.pdf
38. Moore MJ, Early GA. Cumulative sperm whale bone damage and the bends. *Science* 2004; 306:2215.
39. Fernandez A, Castro P, Martin V, Gallardo T, Arbelo M. New beaked whale mass stranding in Canary Islands associated with naval military exercises (Majestic Eagle 2004)? Policy on sound and marine mammals: an international workshop. London, England 2004. http://mmc.gov/sound/internationalwrkshp/postersession.html