High Risk Behaviors in Marine Mammals: Linking Behavioral Responses to Anthropogenic Disturbance to Biological Consequences

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LONG-TERM GOALS

The proposed project focuses on the physiological costs and potential risks of three common responses by cetaceans to oceanic noise, 1) high-speed swimming, 2) elevated stroke frequencies, and 3) rapid ascent from depth. By combining data from previous studies as well as from the proposed experiments, we will provide the first comprehensive evaluation of biological safety zones for diving marine mammals. In this way we intend to identify those marine mammal species or specific attributes of each species that are associated with susceptibility to acoustically mediated disturbance and tissue damage. Furthermore, by identifying high risk and low risk behaviors, and the specific triggers for tissue injury and cardiac instability, we will accomplish the overall objective of improving the protection of marine mammals during naval operations.

OBJECTIVES

We are testing the hypothesis that extreme behaviors requiring marine mammals to perform outside of preferred physiological states represent a graded risk to metabolic and cardiovascular homeostasis during diving, and account for species-specific vulnerabilities to anthropogenic perturbation. Four specific aims are being addressed:

1. Determine physiological costs and risks of high speed behaviors
Recognizing the importance of the mammalian flight response to novel stimuli, we are conducting the first evaluation of the metabolic consequences of high speed performance during diving in a cetacean, the bottlenose dolphin (*Tursiops truncatus*). Indices of dive capacity (aerobic duration, recovery rate, and number of strokes and heart beats in relation to aerobic dive limits) will be defined.

2. Evaluate species-specific costs and cardiovascular risks of high stroke frequency responses
Because the movement of gases (oxygen, carbon dioxide, nitrogen) and metabolic byproducts (lactic acid) depends on heart rate, and the latter is correlated to stroke frequency in marine mammals, we are examining how high performance stroke mechanics (frequency and amplitude) may be linked to tissue

injury via cardiovascular performance during submergence. Neuro-protection through globin deposition and capillarity at the tissue level as well as the impact of high intensity performance on heart rate will be compared for swimming and diving specialists including dolphins, beluga whales, narwhals and foraging Weddell seals.

3. Determine risks and safety zones for rapid ascents by marine mammals

The effects of high speed ascents on cardiovascular stability in cetaceans are being examined by assessing patterns in inter-beat intervals and incidence of arrhythmias from ECGs recorded continuously during vertical sprints by bottlenose dolphins. Comparable tests conducted on trained dolphins in pools and open water as well as on wild narwhals will enable us to identify "safety zones" for cardiac stability related to depth and segment of the dive for different cetacean species.

4. Integrate energetic and cardiac risk factors for development of 3-D safety zones for diving marine mammals

To promote the incorporation of data from these studies into US Navy environmental programs we intend to develop several predictive models integrating depth with physiological capacity and stability for different classes of diving marine mammals. Model elements include allometric relationships for stroking costs, aerobic dive limits, types of neuro-protection (globin deposition, capillarity), and cardiac risk factors that will be mapped on 3-D physical attributes (e.g., home range, hydrostatic pressure) of the marine environment.

Overall, successful completion of the proposed project will allow us to define the major non-disease related factors leading to the observed species-specific propensity for stranding, and enable the development of scientifically-based, environmentally sensitive schedules for naval operations.

APPROACH

This study uses two approaches to determine the relative susceptibility of different marine mammal species to acoustically mediated trauma, 1) tissue/whole animal/physiological exercise assessments to determine the impact of behavioral and environmental challenges to the dive response, and 2) physiological mapping to predict when during a dive and where in the water column marine mammals may be especially vulnerable to anthropogenic perturbation. The following methods will be used:

Part I.

Physiological costs of high speed behaviors

To determine if high speed behaviors impede diving performance by cetaceans, we are conducting measurements of diving energetic costs for bottlenose dolphins using open-flow respirometry. Tests will be conducted on trained dolphins both in pools of varying in depth. We will determine the effect of swimming speed, dive duration, and physical exertion on overall diving costs and recovery. Post-dive blood lactate will be used to evaluate the combination of behaviors that cause the animals to surpass aerobic limits.

Species-specific cardiovascular/high stroke frequency responses

We are using a comparative approach to examine cardiovascular adaptations at both the tissue and whole animal levels that safeguard marine mammals against hypoxic tissue damage when exercising. We will determine the relationship between the deposition of resident globins (neuroglobin, cytoglobin) in the brain, circulating globins (hemoglobin) in the blood, and vascularization for oxygen delivery via the capillaries in swimming and extreme diving specialists including beaked whales, melon-headed whales, narwhals, Weddell seals, and elephant seals. At the whole animal level we will evaluate the interrelationship between stroke mechanics (frequency and amplitude), heart rate variability, and submergence as trained and wild cetaceans wearing a custom-designed ECG-stroke frequency instrument transition from routine preferred levels of exercise to high intensity performance both near the water surface and at depth. Small and large cetacean species will be compared to determine the effects of body size on responses.

Team members include specialists in marine mammal morphology/tissues (M. Miller, CA Dept. Fish and Game; R. Dunkin, UCSC), globin chemists (D. Kliger and R. Goldbeck, UCSC), molecular biologists (M. Zavanelli, UCSC), physiologists (T.M. Williams, D. Casper, N. Thometz and S. Noren, UCSC), and animal behaviorists (T. Kendall and B. Richter, UCSC).

Part II.

Risks and safety zones for rapid ascents by marine mammals

Here we test hypotheses concerning behavioral, physiological and environmental factors leading to cardiac arrhythmias and physiological instability in diving marine mammals. Specifically, we will determine which factors or combination of factors act as the primary instigator of cardiac variability that has been observed for diving marine mammals. Sprint tests will compare the sequential change in inter-beat interval (IBI) of the heart in trained bottlenose dolphins during underwater and surface performances. We will deploy our custom designed ECG-stroke monitor on exercising and diving animals to continuously and simultaneously monitor cardiac and kinematic responses. We will identify, 1) the incidence of arrhythmias, 2) triggers for cardiac anomalies, and 3) the segments of dives (descent, bottom, ascent) associated with cardiac instability.

3-D safety zones for diving marine mammals

To maximize the effectiveness of our data we will develop several quantitative models based on US Navy Decompression Tables that incorporate time at depth, oxygen limitations, nitrogen exchange and ascent rate to delineate the bounds of safe diving conditions for humans, as well as ecological home range models that take into account external environmental and internal animal characteristics to predict movement paths. The resulting stochastic dynamic state variable (SDSV) model will be parameterized with physiological costs and risk factors determined during this project and our previous research. Simulations using the models will be used to develop a physiological-based framework for understanding preferred diving behaviors and depth selection by different marine mammal species, and the effect of anthropogenic perturbation on those behaviors. To broaden the application from individual level to population level consequences, we will provide the input parameters for our models to research groups involved in the construction of Population Consequences of Acoustic Disturbance (PCAD) models.

Team members for this part of the program include physiologists (T.M. Williams, UCSC; R. Davis, Texas A&M University), animal behaviorists (T. Kendall and B. Richter, UCSC; P. Berry, EPCOT) and ecological modelers (R. Dunkin and T. Tinker, UCSC).

WORK COMPLETED

This project began July 2013 with a first year focus on developing the infrastructure for the program. To date this has included, 1) obtaining federal and institutional permitting for all animal use protocols, 2) preliminary assessment and modification of instrumentation for ECG monitoring in comparative marine mammal species, 3) coordination of biomechanics data sets for free-ranging cetaceans with collaborating investigators, 4) training for bottlenose dolphin performance studies, and 5) completion of ECG variability analysis for free-ranging dolphins and seals that form the foundation for this project.

During the past year we have developed and successfully deployed highly sensitive, kinematic-linked ECG recorders on a wild, deep diving cetacean, the narwhal (*Monodon monoceros*), and begun exercise trials with a shallow diving cetacean, the bottlenose dolphin. Importantly, new collaborations with Mads Peter Heide-Jørgensen (Greenland Institute of Natural Resources), Susanna Blackwell (Greenridge Sciences Inc.), Ari Friedlaender (Oregon State University) and Brandon Southall (SEA, Inc., and UCSC) have facilitated comparative kinematic and cardiac analysis for a wide variety of cetacean species for this project. In addition to the physiological studies, tissue level protocols and preliminary work on comparative brain capillarity began during this year and managed by a new post-doctoral researcher, Nicole Thometz.

RESULTS

One of the biggest accomplishments this year was redesign of the electrode system for the UFI kinematic ECG recorder and subsequent testing on a free-ranging, deep diving cetacean (Fig. 1).

Working in collaboration with Mads Peter Heide-Jørgensen we monitored cardiac variability in resting (n = 5 animals) and diving (n = 1) adult narwhals in Scoresby Sound, East Greenland. A custom built ECG recorder with 3- axis accelerometer recorder and pressure transducer was combined with retrieval transmitters (Argos and VHF) and mounted with pressure resistant floatation on suction cups. Dive depths ranged from surface to approximately 250 m with the animals showing marked bradycardia to as low as 10 bpm depending on the depth of the dive. Surface heart rate averaged 78 bpm during the inter-dive interval on the water surface. Heart rate increased during the initial phase of the ascent that corresponded with the period of elevated stroke frequency.

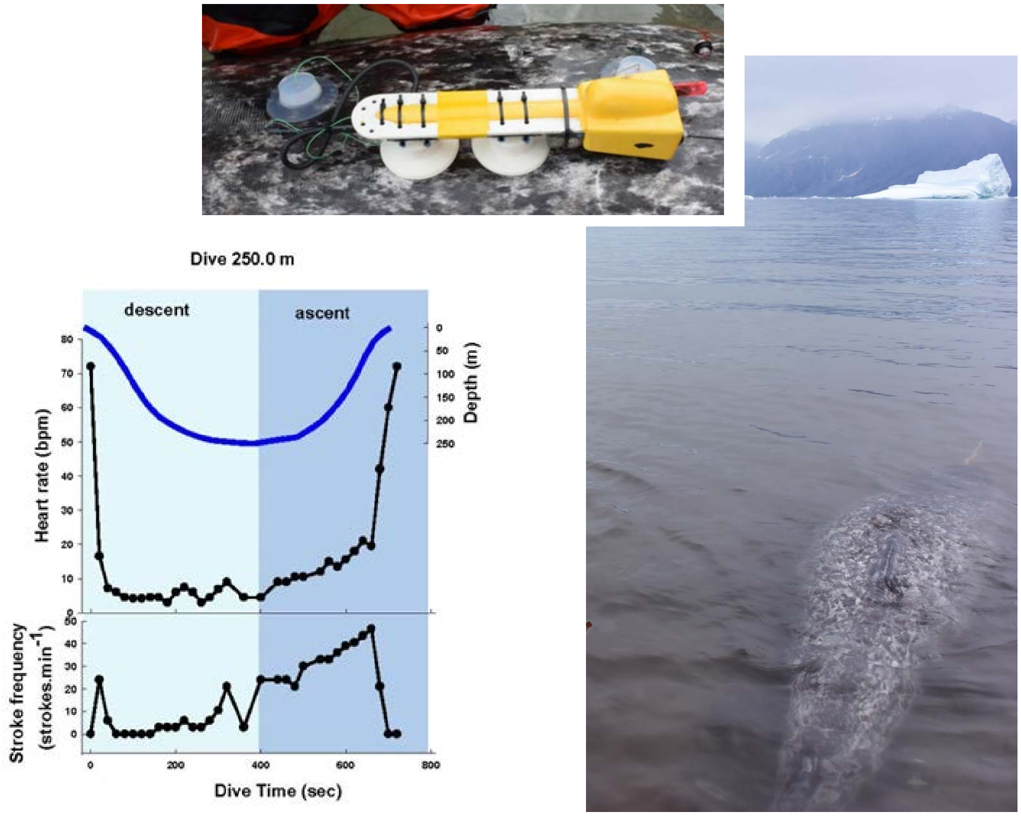

Figure 1. Monitoring heart rate in wild narwhals using ECG- stroke meter instrumentation. The upper panel shows the suction cup electrodes and instrument attachment on the dorsal surface of an adult narwhal (right panel). Changes in heart rate in relation to depth (upper dark blue line), dive duration (upper black line) and stroke frequency (lower black line) are presented for a 250 m dive.

IMPACT/APPLICATIONS

This study will provide one of the first comparative evaluations of biological safety zones for diving marine mammals. In this way we intend to provide data that will help mitigate current misunderstandings regarding lethal and sub-lethal impacts of anthropogenic disturbance on marine mammals by providing a comprehensive understanding of how animals specialized for swimming or diving maintain physiological homeostasis in the face of perturbation. In a novel series of exercise experiments using unique instrumentation on trained and wild cetaceans we will define the energetic costs and physiological risks associated with exercising at depth. By combining data from ongoing and previous studies as well as from the proposed experiments, we will identify those marine mammal species or specific attributes of each species that lead to susceptibility to acoustically mediated disturbance and tissue damage. This will subsequently allow us to achieve our overall goal of enabling Navy personnel to develop schedules for acoustic activities that take into account the potential for lethal and sub-lethal effects on marine mammal populations.

By using a comparative framework incorporating observed behavioral responses to oceanic noise we will provide several tools for other investigators including, 1) stroking costs for different sized cetaceans for free-ranging energetic evaluations, 2) specific behavioral and physiological risk factors for establishment of 3-D geographic/oceanic safety zones, and 3) the development of SDSV and PCAD models that will enable us to make more definitive links between individual species vulnerabilities, population dynamics of diving marine mammals and acoustic disturbances in oceans. In this way the proposed study will produce a dynamic product framework that can be modified as new data and information becomes available with future studies.

RELATED PROJECTS

None

PUBLICATIONS

Terrie M. Williams, Lee A. Fuiman, Traci Kendall, Patrick Berry, Beau Richter, Shawn R. Noren, Michael J. Shattock, Edward Farrell, Andy M. Stamper, and Randall W. Davis (2014) Deep-Sea Sprinting by Dolphins and Seals Challenges the Marine Mammal Dive Response [submitted Nature Communications, refereed]