Improving Attachments of Non-Invasive (Type III) Electronic Data Loggers to Cetaceans

Michael Moore, Alex Shorter, Tom Hurst, and Alessandro Bocconcelli
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
phone: (508) 289 3228 fax : (508) 457 2089 email mmoore@whoi.edu

Mark Johnson and Peter Tyack
Sea Mammal Research Unit
University of St. Andrews
Gatty Marine Laboratory
St Andrews, Fife KY16 8LB UK

Dan Rittschof and Douglas Nowacek
Nicholas School of the Environment
135 Duke Marine Lab. Rd.
Beaufort, SC 28516

Laurens Howle
BelleQuant Engineering PLLC
7813 Dairy Ridge Rd.
Mebane, NC 27302

Award Number: N00014-11-1-0113
http://www.whoi.edu

LONG-TERM GOALS

The overall goal of this project is to increase the longevity of suction cup attachments for short term archival tags such as the DTAG. Specifically, we are working to extend the routine attachment duration for suction-cup tags to multiple days, if not weeks.

OBJECTIVES

Task I: Testing on Animals at Dolphin Quest Oahu – Nov 2012 and Sept 2013
Measure material properties of bottlenose dolphin skin under vacuum loading and identify forces that result in cup failure under controlled loading. CT scans of cups attached to a harbor porpoise cadaver were used to compliment the data collected from live animals.

Task II: CFD modeling for improved tag design
During an on animal attachment the drag forces acting on the tag can remove the package or adversely affect the behavior or energetics of the animal. As such, tag packaging must hydrodynamic to minimize the forces generated by fluid flow. In this part of the work, drag loading of a suction cup tag was analyzed using a computational fluid dynamical (CFD) model.

Task III: Engineered suction cups and surface treatments for improved attachment
Use micro texturing to increase friction of the tag surface against the animal to resist sliding modes of failure. Urethane and silicone samples with high friction micro textured surfaces were fabricated and experimental measurement were made of the modified friction.

Task IV: On-animal performance of tags – Dolphin Quest November 2012
Estimate the modified energetic requirements of an animal due to the increased drag of the tag package. Measurements will be repeated with different tag housings to relate metabolic rate and locomotory effort to housing size and drag. This will also provide a relationship between housing size and skin loading from which to predict the potential for barotrauma. The goal will be to identify tag vs. animal size that minimally alters swimming behavior.

APPROACH

Task 1: Forces and failure modes in suction cup attachments. Define assays to investigate cup failure modes.

Task II: Assessing the impact of tags and surface attachments on cetaceans. Using Computational Fluid Dynamics we will assess the drag forces created by various suction cup and tag housing combinations.

Task III: Engineered suction cups and surface treatments for improved attachment. In the light of Tasks I and II we will engineer suction cups with longer duration using selected materials and molding techniques, cup surface treatments, and investigate the use of adhesives.

Task IV: On-animal performance of engineered attachments and tags. Using free swimming animals, first in captivity and then on stranded releases and animals tagged at sea, we will attach the engineered system with an instrumented cup to test cup behavior and longevity.

WORK COMPLETED

Task I: Testing on Animals at Dolphin Quest Oahu – Nov 2012 and Sept 2013
Method: The smart static suction cup (SSSCup) was used to measure material properties of dolphin skin under pressure loading. The instrument consists of a rigid acrylic half-dome, a molded silicone lip, a linear variable differential transformer (LVDT) to measure displacement of the skin, a pressure sensor and two thermistors. A peristaltic pump creates a controllable vacuum force in the cup and is attached via tubing to a pressure port on the top of the SSSCup. Sensor data are logged using a netbook and USB analog to digital converter. Initial testing of the SSSCup was conducted on a common dolphin (*Delphinus delphis)* cadaver that had been frozen shortly after death, Further testing was conducted at the Chicago Zoological Society, Sarasota Dolphin Research Program's health assessment (May 2012), and at Dolphin Quest Oahu (November 2012) on bottlenose dolphins (*Tursiops truncates)*. Three vacuum profiles were used to load the skin. **Test 1,** a step vacuum loading was increased and then decreased to a 0.3 bar differential. **Test 2,** repetitive pressure loading of the skin over three pressure ranges: low (0.5-0.1 bar), medium (0.5-2 bar), and high (0.5 to 3 bar). **Test 3**, static loading at a single pressure differential (0.3 bar). Three sites with varying anatomical substructure were examined on both the live animals and the cadaver: **Site (1)** the back of the animal, a location with significant subcutaneous fat; **Site (2)** above the pectoral flipper, which overlies muscle inserting

on the blade of the scapula; and **Site (3)** near the dorsal fin insertion, with increased blubber fiber content as part of the dorsal fin saddle.

To measure forces that result in cup failure custom electronics simultaneously measured the applied load and internal pressure in four suction cups. The setup consists of a load cell and five pressure sensors (four to measure internal cup pressure and one for atmospheric pressure). Sensor data are logged using a netbook and USB analog to digital converter, all of which are housed in a portable waterproof container. The cups were loaded to represent drag loading on the cup (applied force parallel to the attachment surface) and lift loading (applied force perpendicular to the attachment surface). Measurements of an individual cup and arrays of cups were made on cadavers, additionally individual cup failure forces were measured on live animals. Measurements were made at the same three sites described in the SSSCup protocol.

To explore the behavior of suction cups under pressure loading a computed tomography (CT) scan of the cup/animal system were made on a harbor porpoise cadaver in the WHOI hyperbaric chamber.

Task II: CFD modeling for improved tag design
See previous reports and paper in press Marine Mammal Science.

Task III: Engineered suction cups and surface treatments for improved attachment
Method: High friction urethane and silicone with a number of micro textures were fabricated for testing. All structures chosen had relatively low aspect ratio with height/width ranging from 1/7.5 to 1.1/1. Low aspect ratio prevents texture buckling and so helps surface deformation mainly occur on the attachment surface rather than the sample. A sled test was used to measure the friction of the samples on against wetted (tap water) neoprene rubber (a stand in for cetacean skin. A normal force was applied to the sample using a flat box with weight, and the pull force was created using weights attached to the sample using a thread that moved over a pulley. The normal (F_N) and pulling (F_{Pull}) forces were heuristically selected to induce consistent sliding for both smooth and textured silicone samples to make velocity readily measurable. Polyurethane slid consistently on wet neoprene with a normal force $F_N = 0.74$ N (76 g load) and pull force $F_{Pull} = 0.83$ N (85 g load). For silicone samples, a more appropriate normal force was $F_N = 0.78$ N (80 g load) with a pull force $F_{Pull} = 0.68$ N (69 g).

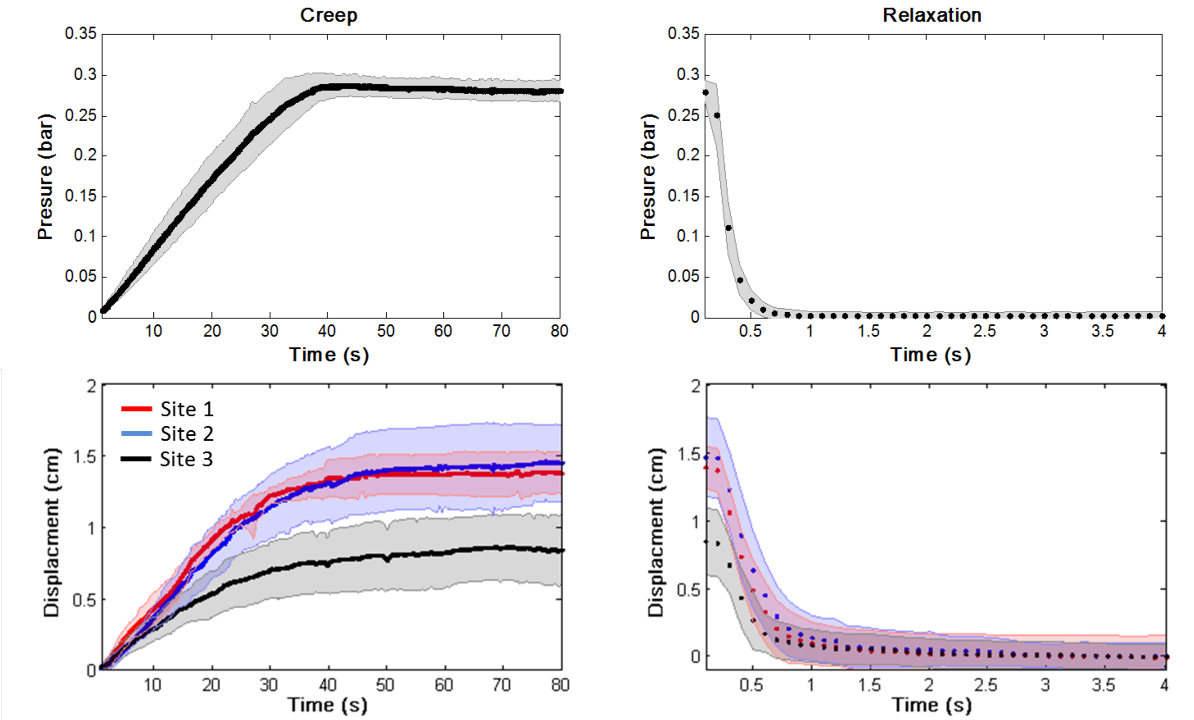

Figure 1 Top: Average pressure loading from all animals and all sites (27 trials), shading shows standard deviation. Bottom: Average displacement data from all animals at each site (9 trials each), shading shows standard deviation.

Task IV: On-animal performance of tags – Dolphin Quest November 2012

Methods: For the testing conducted in November 2012, four captive male *T. truncatus* were trained to swim a set course, with and without tags (DTAG2 and DTAG3 dummy, and surface exclusively in a metabolic dome. Metabolic rate was measured for the duration of each trial, consisting of rest, swim, and recovery phases. Animals were stationary in the dome during rest and recovery phases. The swimming course consisted of a 44 m loop from and to the dome. Each trial consisted of a series of 2-2-1-1 laps, with two to three breaths in the dome between excursions. Animals were reinforced throughout the trial with positive encouragement and tactile stimulation, and with food late in the recovery phase. Tags were attached by hand on the dorsal midline halfway between the blowhole and dorsal fin. A floating transparent acrylic dome (59 L internal volume) was used to collect respiratory gases and determine of the rate of oxygen ($V\ O_2$, $L\ O_2\ min^{-1}$) and carbon dioxide consumption ($V\ CO_2$) by flow-through respirometry. A mass flowmeter (Flow Kit Model FK500, Sable Systems Int.) pulled air through the dome at a flow rate between 400 - 500 $L\ min^{-1}$, automatically correcting flow rates to standard temperature and pressure (STP). A subsample of this gas was passed via Nafion tubing to fast-response O_2 and CO_2 analyzers (ML206, Harvard Apparatus) and data recorded at 2 Hz and saved to a laptop computer. The gas analyzers were calibrated before and after the experimental trials using a commercial mixture of 5% O_2, 5% CO_2, balance N_2, and before and after each experiment using ambient dried air. Mass-specific $V\ O_2$ and VCO_2 ($L\ min^{-1}\ kg^{-1}$) were averaged over phases of pre-exercise rest, exercise, early recovery (0-2 min after exercise), and recovery (0-5 min after exercise). Two-way ANOVA without interaction were used to compare metabolic parameters (VO_2, COT, and LC) during specific phases between tagged vs. non-tagged conditions for each individual. To determine whether the metabolic data were sensitive to temporal binning, a logarithmic function was fit to the inspired O_2 measurements for each trial and compared the slope and intercept coefficients of tagged and non-tagged trials. Swimming speed was estimated by dividing the distance of the swimming track by the time required for an individual to complete the lap. Two-way ANOVA were used to compare swimming speeds observed in tagged vs. non-tagged conditions for each individual. A linear function was fit to the swimming speed during every lap set to determine whether speed decreased throughout the duration of the trial, and the slopes of these regressions compared with two-way ANOVA.

RESULTS

Task I: Testing on Animals at Dolphin Quest Oahu – Nov 2012 and Sept 2013

Representative data from both Sarasota and Hawaii (n = 9) for the creep/relaxation testing have been compiled in Figure 1. Loading is shown on the right and unloading on the left. During the failure testing, the array of cups on the cadaver failed under drag loading at significantly smaller forces than during lift loading. Additionally, the failure forces were variable depending on the attachment site. In addition to the cadaver work with tag models, the failure forces of individual suction cups on live animals were examined at Dolphin Quest. As with the cadaver work, the failure force that results in sliding on the animal is much lower than the force that results in a detached cup during lift loading.

The WHOI hyberbaric chamber was used to examine the effect of increased ambient pressure (up to 180 psi) on the cup/skin system. The resulting images show that the air in the cup internal volume and stem has mostly collapsed by 60 psi and is no longer visible at 180 psi anywhere. Air does not completely expand in the internal volume after the tube pressure returns to zero. The change in the cup and skin geometry is an indication of tissue ingress into the cup.

Task II: CFD modeling for improved tag design

See previous reports and paper in press Marine Mammal Science.

Task III: Engineered suction cups and surface treatments for improved attachment

Texturing on both the urethane and silicone samples resulted in a significant reduction of the sliding velocity of the samples. The urethane, with the grooves orthogonal to the pulling force, reduced sliding velocity by ~90%. A square texture pattern on the silicone reduced sliding velocity by ~75%.

Task IV: On-animal performance of tags – Dolphin Quest November 2012

Individuals showed no difference in metabolic cost under tagged vs. non-tagged conditions for any of the four phases ($p > 0.1$). Further, the swim/rest periods did not differ between tagged and non-tagged conditions ($p = 0.9315$). Slopes ($p = 0.5716$) and intercepts ($p = 0.5919$) of logarithmic functions fitted to inspired O_2 curves did not differ significantly between tagged and non-tagged trials. Individuals did not show significantly higher total or net cost of transport in the tagged condition (COT, $J\ m^{-1}\ kg^{-1}$) (two-way ANOVA, $p = 0.5239$ and 0.1377 respectively), nor did tagged individuals have greater locomotory costs (two-way ANOVA, $p = 0.2937$). However, tagged animals swam on average 0.35 (95% CI 0.01 – 0.70) m/s slower than non-tagged animals (two-way ANOVA, $p = 0.0441$.

ACKNOWLEDGEMENT

Many thanks to Julie Rocho and the whole Dolphin Quest team for the support for this part of the project.

IMPACT/APPLICATIONS

Task I: Testing on Animals at Dolphin Quest Oahu – Nov 2012 and Sept 2013
The lift and drag forces generated by the tag must be resolved at the point of attachment if the tag is to remain on the animal. Cup detachment is likely to be a complex function of the loading and the substrate shape and properties, and so will not occur consistently at a predictable speed.

Task II: CFD modeling for improved tag design
See previous reports and paper in press Marine Mammal Science.

Task III: Engineered suction cups and surface treatments for improved attachment
The neoprene surface has random low aspect ratio surface texturing that does not match up with the urethane ridges nor the silicone pillars. This indicates that the mechanism that increased friction in this work was not an interlocking effect between the micro textures and the neoprene, but that the surface textures increased friction between the sliding surfaces by deforming the neoprene on the microscale. From these results we infer that as the surfaces move past each other more energy was required to move the deformed neoprene around the harder textures.

Task IV: On-animal performance of tags – Dolphin Quest November 2012
While these preliminary results do not demonstrate a significant difference between tagged and untagged swimming, reduced velocity suggests that tagged animals may be modulating swim speed to maintain metabolic output and energy expenditure when faced with higher body drag. In future work we will deploy tags of increasing size and drag to identify thresholds beyond which tag size does affect metabolic cost, and to further investigate animal response to increased drag via modulation of kinematics and swimming speed.

PUBLICATIONS

I. Presented at the APS-Division of Fluid Dynamics meeting in San Diego, CA 2012.
Numerical and experimental hydrodynamic analysis of suction cup bio-logging tag designs for marine mammals M.M. Murray, K.A. Shorter, L. Howle, M. Johnson and M. Moore.

II. Accepted for the Society for Marine Mammology's biennial conference in Dunedin, New Zealand December 2013.
Sticking it to the Whales: Adhesive Attachment of Biologging Devices to Cetaceans
M. Bowers, D. Rittschof, D. Nowacek, T. Austin, K. A. Shorter, T. Hurst, M. Moore

Metabolic and kinematic effects of tag attachment in *Tursiops truncatus*
J.M. van der Hoop, A. Fahlman, T. Hurst, T., Shorter, K.A., M.J. Moore.
III. Accepted for Acoustical Society of America's meeting in San Francisco, CA Dec 2013.

The next generation of multi-sensor acoustic tags: sensors, applications and attachments
Nowacek, D.P., Bowers, M., Cannon, A., Hindell, M., Howle, L.E., Murray, M.M., Rittschof, D., Shorter, K.A., and Moore, M.

IV. The following manuscript has been accepted for publication in Marine Mammal Science.
Drag of suction cup tags on swimming animals: modeling and measurement
K.A. Shorter, M.M. Murray, M. Johnson, M. Moore and L.E. Howle