Improving Attachments of Remotely-Deployed Dorsal Fin-Mounted Tags: Tissue Structure, Hydrodynamics, In Situ Performance, and Tagged-Animal Follow-Up

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LONG-TERM GOALS

We recently developed small satellite-linked telemetry tags that are anchored with small attachment darts to the dorsal fins of small- and medium-sized cetaceans. These Low Impact Minimally-Percutaneous External-electronics Transmitter (LIMPET) tags have opened up the potential to monitor the movements of numerous species not previously accessible because they were too large or difficult to capture safely, but too small for tags that implant deeply within the body. One goal of this project is to improve upon our existing tagging methodology to achieve longer, less variable attachment durations by carefully examining the factors that affect attachment success. Our key goal is to develop a method for attaching tags to cetaceans that provides the data needed to answer critical conservation and management questions without an adverse effect on the tagged animal. Therefore, we will also conduct follow-up studies of whales that have been tagged with a remotely-deployed dorsal fin-mounted tag to accurately quantify wound healing and the effects of tagging on whale survival, reproduction, and behavior. The combination of these approaches will provide an improved understanding of some of the key factors affecting tag attachment duration as well as a more complete understanding of impacts to individuals due to tagging.

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OBJECTIVES

1. Design an improved barnacle-style tag shape for remote-deployment by assessing the hydrodynamic properties of tag shapes
2. Examine the tissue structure of the dorsal fin and its material properties for better informed implanted attachment design.
3. Examine the in situ performance of our current attachment devices and then design and test improved retention systems
4. Conduct follow-up studies of tagged whales to accurately quantify wound healing and the effects of tagging on whale survival, reproduction, and behavior

APPROACH

1. Hydrodynamics of tag shape (Key individuals: Mittal, Howle, Andrews, Schorr, Hanson): We will determine the drag on the tag through numerical modeling and analysis, primarily computational flow dynamics. High fidelity numerical simulations working in concert with physical experiments will be used to establish qualitative as well as quantitative relationships between tag configuration and the associated flow structure and surface pressure distribution, which is ultimately the key to the force/moments on the tag.

2. Dorsal fin tissue structure (Key individuals: Hanson): To evaluate the factors influencing tissue degradation (and therefore attachment duration) we will assess the anatomical factors likely to influence long-term viability. Interspecific differences in these parameters may be an important factor in the variability in attachment duration, as might body size scaling effects. We selected various species for examination based on differences such as size/shape of the dorsal fin (e.g., melon-headed versus killer whale), taxonomic grouping (i.e., odontocetes versus mysticetes), or dynamic behavior (*e.g.*, beaked whale versus melon-headed whale).

3. Performance of tag attachments – simulated and actual (Key individuals: Andrews, Schorr, Hanson, Howle, Mittal): A key factor in attachment duration is likely the hydordynamic forces imposed by the tag body but acting on the attachment elements implanted into the dorsal fin. Although we have a good idea of how the LIMPET retention system operates when first implanted, we do not fully understand the mechanics in a living fin. Therefore, we will use non-invasive imaging of carcass tissue to determine how the retention elements behave in situ. These results, along with those from the analysis of dorsal fin histology and material properties will inform modified designs. Hundreds of LIMPET tags have now been applied to various species of cetaceans, and we will examine inter-species differences and explore factors that effect tag longevity.

4. Tagging effects - follow-up studies of survival, reproduction,& behavior (Key individuals: Baird, Schorr, Andrews, Hanson): More thorough assessments of the potential impacts on survival and reproduction of individuals, as well as assessment of healing of the tag attachment sites and potential behavioral changes associated with tagging, are needed to address concerns regarding sub-lethal and potentially lethal impacts of remotely-deployed tags. As part of an ongoing collaborative study, over 130 satellite and VHF tags have been remotely-deployed on 9 species of odontocetes around the main Hawaiian Islands. Re-sighting rates for the two species with the largest sample size of tag deployments, short-finned pilot whales (n = 48 individuals) and insular false killer whales (n = 27 individuals), are particularly high, as populations are small, individuals are relatively easy to approach, and there are sufficient encounters each year to have a high probability of re-sighting previously tagged whales. We will assess impacts of remotely-deployed tags on tagged animals at a variety of levels: from wound healing and potential behavioral effects of tag attachment to reproduction and survival. Assessment of reproduction and survival of tagged whales will utilize existing photographic datasets as well as additional photos taken during this project.

WORK COMPLETED

Objective 1:
Computational Fluid Dynamics (CFD) studies were undertaken to compare the most recent iterations of the LIMPET tag designs, the location-only AM-240C tag and the dive depth-transmitting AM-292C tag. The studies included a flow speed sweep at a fixed orientation, a yaw angle study (tag rotated about a vector normal to the mounting surface), a pitch angle study (tag rotated about a vector that was the cross product of the free-stream flow direction and the mounting surface normal vector), an offset study (offset = distance from the bottom of the tag and the dorsal fin or surrogate mounting surface), and a study combining pitch and yaw. CAD models of the two tag types, in SolidWorks format (Fig. 1), were provided by Shawn Wilton of Wildlife Computers and were imported directly into the SolidWorks Flow Simulation CFD package.

Objective #2: Histological slides of the horizontal cross section of the central section of dorsal fins from five species of cetaceans - pilot whale, killer whale, melon-headed whale, Bryde's whale, Cuvier's beaked whale, and Blainville's beaked whale – were developed to assess geometry and collagen composition of primary structural layers. Percent composition of the three structural layers (i.e., collagen bearing layer); sub-papillary layer, vertical sheath and central core was measured using image analysis software for each of these species. In addition, the killer whale fin was sectioned in five locations to assess structural variability in different areas of the fin where tags have been deployed (Fig. 6). Material properties of the two primary collagen bearing layers of the dorsal fin (ligamentous sheath and central core) were measured for the species previously noted on a uniaxial tester. Stress/strain curves were developed for these layers in various orientations (ligamentous sheath; dorsal/ventral, anterior/posterior, central core; dorsal/ventral, anterior/posterior, lateral).

Objective #3:
Assessment of tag attachment durations: To assess differences in durations by a certain attachment variables, including tag mold and dart design, analyses were restricted to species with 15 or more successful SPOT5 deployments. Criteria included; Tag was attached with long (6.7 cm penetration depth) darts and had both darts implanted (deployments with only one dart implanted were significantly shorter [median =14.9d, n=6, versus a median of 40.8d, range = n = 91, Mann-Whitney U-test, p = 0.004]) , was not documented to be cracked on impact, was deployed in the dorsal fin (not in blubber of flank), and was not known to have tag-related problems (e.g. electronic or software bugs). This filtered out all species except False Killer Whales (FKW), Fin Whales (FW), Killer Whales (KW) and Short-finned Pilot Whales (SFPW). FW transmission durations were significantly shorter than the other species (Kruskal-Wallis multiple comparison, p = 0.0004, Z-value > 2.836) and much more variable, so they were excluded from further tests. Variables assessed were: vertical and horizontal placement, orientation, 'flushness' of deployment (i.e. the degree of levelness between the plane of the bottom of tag and the fin plane), number of darts through the fin, distance between tagger and whale, age class and sex. Where sample sizes of one particular variable were too small, they were removed from that particular test. Additional analyses were conducted on the subset of deployments that were greater than 50 days to assess what factors might be leading to longer transmission durations.

Attachment variables between false killer whales (median duration =51.9 days, range = 6.3 - 199.0, n= 20), and fin whales (median duration = 21.7, range = 0.1 - 179.2, n = 42) were compared to assess possible reasons for the significant difference in duration.

Ballistic Testing: Tests were conducted to compare flight characteristics between tag types, and to assess different pneumatic air rifle designs and delivery arrows. Two air rifles were tested; the Dan-Inject JM Special 25 bar with a 13mm barrel (the device used in 96% of our deployments), and a Dan-Inject JM Special 25 bar modified to fit a 20mm barrel. The larger bore diameter of the 20mm Dan-Inject allowed the addition of flights and other larger stabilizers to be added to the back of the arrow, in an effort to stabilize the arrow in flight and reduce the tag-down flight orientation of the current design. Additionally, the arrow leaves the barrel with higher velocities than the 13mm barrel, meaning deployments at further distances may be attempted. Arrow end designs tested are shown in Fig. 8). The rifle was placed in a rifle rest for consistency. Flight angle was determined using a high-speed video camera to capture the arrow just prior to impact with the target, and measuring the angle of the arrow compared to horizontal. Negative values indicate that arrows flew with the front (tag) end below the horizontal plane. Velocity of the tag was measured at 0.25m from the barrel of the rifle, and at 1 m in front of the target.

Objective #4:
In FY13 work was directed at four tasks. 1: Obtaining additional follow up photos from collaborators and through projects funded for other purposes. 2: Matching of photos for species that had been satellite tagged for addition to our long-term photo-ID catalogs. 3: Association analyses to identify stable groupings (“clusters”) and assessments of re-sightings and reproduction of tagged individuals. 4: quantitative estimation of survival of tagged and non-tagged individuals using a capture-recapture framework, for the two species with the largest samples sizes of tags deployed and photo-identifications (false killer whales and short-finned pilot whales).

Field projects funded by other sources were undertaken off Hawai‘i Island in May 2013, off Lāna‘i in December 2012, and off Kaua‘i in February, July, and August 2013, and photos were obtained from collaborators off O‘ahu and Hawai‘i Island. All photographs obtained through Aug. 2013 of 4 of the 8 tagged species with photo-ID catalogs (false killer whales, pygmy killer whales, Cuvier’s beaked whales, Blainville’s beaked whales) have been matched to our catalogs to identify previously tagged individuals. All photos of Hawai‘i Island resident melon-headed whales have been scanned for re-sightings of tagged individuals. Photos of short-finned pilot whales from Hawai‘i Island through May 2013 have been added to the catalog, prioritizing groups known to contain tagged individuals. Analyses of re-sighting periods are from the time of last known transmission or known tag loss (hereafter referred to as post-tag loss).

For false killer whales, the sample used for quantitative estimation of survival of tagged and non-tagged individuals included 142 distinctive and very distinctive individuals photo-identified between 2003 and 2013, with a total of 1,280 records. The dataset contained the re-sighting (capture) histories of 24 distinctive or very distinctive individuals that had been satellite tagged between 2007 and 2011. One of these had been tagged twice, for a total of 25 tag deployments. Three social clusters were identified, with tags deployed on individuals in two of the three clusters (Baird et al. 2012). For short-finned pilot whales, the photo-identification catalog contains 620 distinctive and very distinctive individuals from 34 different social clusters off Hawai‘i Island between 2003 and 2012, with a total of 6,094 records. Of these, 46 individuals were satellite tagged between 2006 and 2012, in 15 different clusters containing 335 individuals. For these 15 clusters there were a total of 4,763 records. Five of these individuals were tagged twice for a total of 51 tag deployments. For both species analyses were restricted to distinctive and very distinctive individuals with good or excellent quality photos (Baird et al. 2008; Mahaffy et al. in review).

RESULTS

Objective 1:

Flow speed study: CFD simulations were conducted at flow speeds of 0.75, 1.50, 3.00, 5.00, and 7.00 m/s. For this flow speed study, the tags were aligned with the oncoming flow (yaw angle = pitch angle = 0 degrees). In Figure 2, we show the drag force as a function of flow speed, demonstrating the characteristic quadratic dependence of drag with flow speed. Note that the AM-292C tag has slightly greater drag over the range of flow speeds considered. The lift force, similar to the drag force was slightly greater for the AM-292C tag than for the AM-240C tag (Fig. 2).

Yaw angle study: We define the yaw angle as a rotation about the mounting surface normal vector. CFD simulations were performed for yaw angles of 0, 45, and 90 degrees at a fixed flow speed of 1.5 m/s. Both tags showed an increase in drag (Fig. 3, left) with yaw angle. This is consistent with expectations as the 90 degree yaw orientation presents a greater projected area to the oncoming flow. The lift force (Fig. 3, right), first increases and then decreases with yaw angle.

Pitch angle study: The pitch angle (Fig. 4) was defined as positive when the leading edge lifted away from the mounting surface. For this study, the flow speed was held constant at 1.5 m/s and the yaw angle was fixed at 0 degrees. Increasing the pitch angle increases the drag force (Fig. 5, left). This approximately 2.5x increase over the pitch angle range of 0 to 40 degrees results from increased projected frontal area with increased pitch angle. In contrast to the drag force, the lift force (Fig. 5, right) did not show a monotonic trend over this same range of pitch angles for both tags. The AM-292C tag generated increased lift for 0 and 20 degree pitch angles whereas the AM-240C tag generated increased lift at 40 degrees.

Offset study: An offset study was performed at two offset heights, 0.01in and 0.25in. Offset was defined as a gap between the mounting surface and the lower surface of the tag housing. Both tags showed similar results with gap increased from 0.01in to 0.25in. For both tags, the lift force dropped off while the drag force showed little change. The AM-24C tag had a lift force of 0.6915N at 0.01” offset, but dropped by 72%, to 0.1942N, at 0.25” offset. Lift force dropped by 59% with the increase in offset, from 0.8413N to 0.3415N.

The CFD comparison of the AM-240C and AM-292 tags indicated that the AM-292C tag generated somewhat higher lift but primarily at flow speeds above 5 m/s and aligned flow (0° yaw angle). The AM-292C tag also generated somewhat higher drag than the AM-240C tag. At a fixed flow speed of 1.5 m/s both tags showed a fairly weak dependence of lift and drag on yaw angle. Both tags demonstrated an increase in drag of approximately 2.5x for pitch angles up to 40°. As shown in our previous studies, an increase in gap (offset) from almost touching the mounting surface to about 0.3 times the height of the tag, caused a shift from lift-dominated to drag-dominated force. Overall, the AM-240C tag produced somewhat lower lift and drag than the AM-292C tag for most of the flow scenarios considered.

Objective #2: Estimates of collagen composition were slightly higher in the recent analyses (2-14%) for the same slides that were measured in 2011. The increase may be due to a small instrumentation change, which is currently being investigated. Percent collagen in the ligamentous sheath was consistently high in all species, ranging from a high of 96% in the pilot whales to a low of 75% in Blainville's beaked whales. Inter-species variability was greater for the central core where the pilot whale again had the highest percentage of collagen (81%), but the Blainville's beaked whale was lowest at 42%. For the killer whale fin, the central and anterior regions in ligamentous sheath had highest percent collagen while the dorsal and posterior areas had uniformly high percent collagen in both layers.

The ligamentous sheath (dorsal/ventral orientation), showed post-transitional phase slopes that were relatively similar, except for Melon-headed whale (Figure 7). Peak stress before failure was highest in melon-headed whale. Post-transitional phase slopes of ligamentous sheaths did not correspond well with percent collagen except for melon-headed whale. The two highest percent collagen species, pilot whale and killer whale had the two lowest strength curves. Similarly for the central core, the post-transitional phase slopes of this layer were relatively similar, except for Melon-headed whale. Peak stress before failure was highest in Blainville's beaked whale. Like the ligamentous sheath, post-transitional phase slopes of the central core correspond almost inversely with the percent collagen illustrated by Blainville's beaked whale being the highest and pilot whale and killer whale the lowest. For the comparison of the different regions within the killer whale fin, the dorsal-most area had the greatest strength in the ligamentous sheath (dorsal- ventral orientation) and ventral section the weakest, with the other regions slightly stronger than the ventral. The anterior region of the central core (anterior- posterior orientation) had the greatest strength of the five regions, the ventral and posterior the lowest, and dorsal and central the intermediate. Our next step is to compare these anatomical and functional properties with the performance of the LIMPET tags in the various species (see Objective 3).

Objective #3:

Tag attachment durations: There was no significant difference in transmission duration by tag version for SPOT5 tags (Kruskal-Wallis multiple comparison, $p = 0.128$, Z-value < 1.95, $n = 88$), or by dart version (Kruskal-Wallis, $p = 0.160$, Z-value < 2.47, $n = 88$), though the newest version of the dart (WC-Stnd-Rev4) had the longest transmission duration (Fig. 9). To better assess the recent change in the dart manufacturing process, we conducted a restricted analysis to the most recent tag version (AM-240C). The new dart type resulted in significantly longer transmission durations, with the old dart having a mean of 28.4 days (sd = 22.4, n = 11) and the new dart a mean of 68.3 days (sd = 30.2, n =5) (two-sample T-test, $p = 0.005$). While sample sizes are small, this suggests a dramatic improvement in the dart design. For all other variables tested, there was no significant effect on transmission duration except for sex (weakly significant, Aspen-Welch unequal-variance, $p = 0.048$) and flushness, where tags with a leading edge up orientation (positive pitch angle) had significantly shorter durations than tags which were flush (Kruskal-Wallis multiple comparison, $p = 0.015$, z-value = 2.919). Using a multivariate analysis of variance, sex was no longer significant, but flushness was significant ($p = 0.0205$), with tags in the leading edge up orientation having a mean duration 12 days shorter than other categories (Fig. 10). These results suggest that despite a large number of variables that may influence transmission duration, tags deployed with their leading edge lifted up into the flow have the shortest attachment durations, consistent with results from the hydrodynamic studies that demonstrated large increases in drag at positive pitch angles.

We assessed the difference between the species with the longest median transmission duration, false killer whales (FKW) and the species with the shortest transmission duration, fin whales (FW), a difference that was highly significant. Only three of the FW tags deployed had the leading edge up, so that likely doesn't explain the difference in durations. While sample sizes are small for FW, there was a dramatic, albeit barely significant, difference in transmission duration by sex, with females having a mean of 54.3 days (sd = 36.7, n = 4) and males 12.1 days (sd = 10.3, n =5; Two sample T-test, p = 0.04), suggesting a possible gender-specific behavioral explanation for the sex difference in fin whales. Besides behaviors that could disrupt the tags, causes for the duration difference between FKW and FW could include differences in fin tissue structure, or other external forces such as drag and lift. The mean horizontal rate of movement for tagged FWs = 2.72 km/hr (n = 58) (CRC unpublished data) versus 5.03 km/hr (n = 7) for FKW (Baird et al., 2008). This suggests that hydrodynamic forces such as drag and lift are not likely to be the driving cause behind shorter transmission durations for fin whales. We assessed tags which transmitted for 50 days (n = 36) or more to see if there was one factor that was significantly associated with longer deployments. None of these "long" deployments had a "leading-edge up" orientation, and 27 of the 36 tags were deployed "flush" to the fin.

Ballistics: The SPOT5 (AM-240C) tag had a mean elevation drop of 22.4cm (sd = 1.67, n = 19) when the distance to the target was increased from 10 to 15m, while the Mk10-A (AM-292) tag had a mean drop of 25.4 cm (sd = 3.07, n = 32). So when shooting the heavier Mk10-A tag at 15m, the tagger must account for an additional 3cm drop over the SPOT5 tag at the same distance. Windage differences between the tags were even greater, at 15m, likely caused by the significantly slower at-target velocity of the Mk10 than the SPOT5 tag (9% slower at 15m). None of the variations in the arrow designs tested resulted in significant improvements in flight trajectory or precision, although arrow m007 with the "air brake" tended to be more precise.

While variables such as tag shape, rotation during deployment, and exact placement on the fin don't appear to play large roles in transmission duration, a positive pitch angle (leading edge up) significantly reduces transmission duration. The two factors most likely to result in a leading edge up deployment are 1) deploying a tag when the plane of the dorsal fin is not perpendicular to the line of flight or 2) yaw of the arrow in flight which could be induced by factors such as wind or hydrodynamic properties of the arrow and/or tag. Therefore it is worthwhile to explore tag shapes whose drag and lift forces are impervious to variances in pitch angle. In our examination of the tag shape characteristics, we have concentrated on tag hydrodynamics, and have largely neglected aerodynamics. The large overall variability in tag attachment durations combined with some specific clues from certain species (e.g. fin whales), suggest that stochastic behavioral issues may be causing the majority of tag attachment failures, and not the simple pull of the drag and lift forces over time. Therefore, further exploration of aerodynamics is warranted because it may result in increases in our ability to precisely place the tags, especially on species with small fins or ones that are difficult to approach within 10m.

Objective #4:

The proportion of individuals re-sighted post-tag loss was relatively high even for infrequently encountered species (see Baird et al. 2013 for information on encounter rates). Pygmy killer whales have the lowest overall encounter rates of tagged insular species (Baird et al. 2013), yet five of the seven (71%) pygmy killer whales tagged prior to 2011 were re-sighted at periods from 2.81 – 4.62 years post-tag loss. Two of the tagged pygmy killer whales were known to be females based on genetic analyses of biopsy samples: of these, one was known to have had a calf born post-tag loss. Three distinctive melon-headed whales from the Kohala resident population were tagged prior to 2012, and two of the three (67%) were re-sighted post-tag loss at periods of 0.8 to 2.7 years. For Cuvier's beaked whales, six of 10 tagged individuals were re-sighted post-tag loss at periods ranging from 0.75 to 1.91 years. Re-sighting probability for male beaked whales is lower than for females (McSweeney et al. 2007); of the four known adult females tagged, three have been re-sighted (75%). Two of the three re-sighted females had small calves with them when they were re-sighted at 1.5 and 1.8 years post-tag loss. Of the 10 insular Blainville's beaked whales (see Baird et al. 2011) tagged prior to 2011, seven (70%) were re-sighted post-tag loss at periods ranging from 0.01 to 3.66 years. Blainville's beaked whales have known higher dispersal rates for males than females (McSweeney et al. 2007). An assessment of the proportion of adult females re-sighted indicated 6 of 7 females from the insular population (85.7%) were re-sighted post-tag loss from 0.77- 3.66 years.

Assessing reproduction of previously tagged whales of all species is limited by the relatively small number of known adult females tagged, the typically long inter-birth intervals for most species, and the long intervals between re-sighting events. For some species, e.g., melon-headed whales, no known adult females have been tagged. The only species with females known to have given birth post-tagging are pygmy killer whales (one of two tagged females have given birth post-tag loss) and Cuvier's beaked whales (two of the three known adult female Cuvier's beaked whales that have been re-sighted had calves with them born since the females were tagged).

Two species had sufficient sample sizes both of tags deployed and of encounters to quantitatively assess survival of tagged versus non-tagged individuals. In both cases, false killer whales and short-finned pilot whales, association analyses indicate the existence of strong, long-term association patterns with individuals grouping in "clusters" (Baird et al. 2012; Mahaffy et al. in review), so analyses considered cluster as one variable potentially influencing estimates of survival.

Modeling was conducted with R-Mark (version 2.1.5, Laake and Rexstad, 2008), an R package developed to perform estimates of demographic parameters using mark recapture techniques using the engine of software Mark. The main advantage of R-Mark is to allow the development of complex models in a more straightforward and intuitive fashion using standard formula notation in R (as opposed to having to build complex parameter index matrices – PIMS or design matrices in Mark). The analyses were conducted using the Cormack-Jolly-Seber (CJS) (Cormack, 1964; Jolly, 1965; Seber, 1965) model, which presents two main parameters: apparent survival (Phi) and capture probability (p). These parameters were modeled following the typical formulation available in Mark (White and Burnham, 1999) as well as more complex models developed by building design matrices (using R notation) for estimation of parameters as a function of covariates (e.g. a tag effect). The number of proposed models depended on the modeling approach and is specified for each of the analyses below. Model selection was performed using the Akaike Information Criterion for small samples (AICc) after accounting for overdispersion in the data (Burnham and Anderson, 2002). Overdispersion was computed using TEST1 and TEST2 in program RELEASE as a guide for goodness of fit test of a general model with full time-dependant effects (e.g. White and Burnham, 1999). Tag effects were modeled as a time-varying covariate for individuals tagged between 2007 and 2010 (false killer whales) and 2006 and 2012 (short-finned pilot whales). A single false killer whale individual tagged in 2011 was not included in the analysis because the individual was considered only slightly distinctive (Baird et al. 2008).

False killer whales: Two analyses of apparent survival were undertaken, one including all three clusters (approach 1), and one restricted to cluster 1 (approach 2), which had the majority of distinctive individuals (66), tag deployments (16 of 25), and approximately 50% (639 of 1280) records. Cluster 3, which comprised 45 individuals, had nine tag deployments and 193 records. For approach 1, 16 models were run with a combination of potential effects (Table 1). Model selection (Table 2) was performed using QAICc after accounting for overdispersion in the data (estimated c-hat = 1.87) using TEST1 and TEST2 in program RELEASE. For approach 2, restricting analyses to just Cluster 1 individuals, six models were run using a combination of effects. Model selection was performed using QAICc after accounting for overdispersion in the data (estimated c-hat = 2.37) using TEST1 and TEST2 in program RELEASE.

There is little evidence to suggest that the survival probability of tagged false killer whales is reduced relative to untagged individuals, either when modeling all clusters or only cluster 1. The best model in both cases did not show a tag effect. When all clusters are considered the point estimate of the model average survival probabilities is lower for tagged whales, but these estimates are not statistically different from non-tagged whales as indicated by the overlapping confidence intervals. Precision of the estimates of Phi for tagged whales is low likely due to the small sample of tagged whales. When all clusters are considered, capture probability for Cluster 1 individuals is relatively high (mean = 0.56), while capture probabilities for Cluster 2 (mean = 0.28) and Cluster 3 (mean = 0.27) were much lower. When only Cluster 1 is considered (approach 2), the survival estimates for tagged whales is actually slightly higher than for untagged whales, although these estimates are not statistically different, as indicated by overlapping confidence intervals.

Short-finned pilot whales: For short-finned pilot whales, two analyses were run, one taking into account all 34 social clusters (approach 1), and one restricted to the 15 social clusters that contained tagged individuals (approach 2). For the analysis considering all social clusters, cluster was not used as a covariate due to relatively small sample sizes for some clusters. A total of four models were run with a combination of effects. Model selection was performed using QAICc after accounting for overdispersion in the data (estimated c-hat = 3.17) using TEST1 and TEST2 in program RELEASE.

The results of these analyses indicated there is little evidence to suggest that the survival probability of tagged short-finned pilot whales is different from untagged individuals. In the present analysis, a tag effect was present in two of the four proposed models. The model with a tag effect ranked lower than the equivalent one without the effect. The point estimate of the model averaged Phi estimates show the survival of tagged whales being slightly higher than that of non-tagged whales, but the estimates are clearly not significantly different as indicated by their highly overlapping confidence intervals. Precision of the estimates of Phi for tagged whales is low likely due to the small sample of tagged whales. Also, the point estimates of apparent survival is relatively low (~0.9) for a long-lived cetacean such as short-finned pilot whales. The low values are biased because some of the clusters sampled in this study have not been seen frequently. If animals are alive but not often detected, the model interprets them as "dead" and the estimated survival parameter is underestimated. The approach below attempt to deal with this issue by selecting the subset of the short-finned pilot whale clusters that included tagged individuals

For the analysis including only those 15 clusters that included tagged individuals, it was possible to include cluster as a covariate as the number of capture events per cluster was greater. For this analysis a total of 16 models were run with a combination of the effects. Model selection was performed using QAICc after accounting for overdispersion in the data (estimated c-hat = 3.70) using TEST1 and TEST2 in program RELEASE. The survival estimates (~0.96) obtained with approach 2 are more consistent with a long-lived marine mammal such as short-finned pilot whales and therefore are preferred relatively to approach 1. Once again, there is little evidence to suggest that the survival probability of tagged whales is different from untagged individuals. Models with tag effect ranked lower than their equivalent model without this effect. For example, the best model provides a better fit than the equivalent model with a Tag effect. The predicted survival probability for a tagged whale is nearly the same as that of an untagged individual and is clearly not statistically different. Wide confidence intervals of Phi for tagged whales are a result of a relatively small sample size.

Power to detect tag effects: One of the main questions in estimating survival of tagged and non-tagged whales relates to the power of the statistical models to detect the tag effect. In general, cetacean satellite tagging studies have small sample sizes primarily because of the relatively high cost of the instruments. The power to detect a tag effect in capture-recapture studies such as those described above depends on the magnitude of the effect, whether the effect is acute or chronic, the sample sizes (e.g. number of capture occasions, proportion of the population tagged), the capture probability, and the precision of the parameter estimates. One way to assess the power to detect a tag effect for capture-recapture studies is through simulation. Estimates of model parameters such as those provided above can be used to simulate a population under circumstances that match the sampling scheme of the study in order to assess the probability a tag effect is correctly estimated given the parameters and the model structure.

Preliminary simulations assuming a yearly survival estimate of 0.95 for both false killer and short-finned pilot whales and that 2.5% of the population is tagged every year for a period of 10 years were conducted using average values of capture probability consistent with those reported above (p=0.4 for false killer whales and p=0.7 for short-finned pilot whales). These simulations show that high probabilities to detect a tag effect require significantly large tag effects. In the example provided above, mortality has to increase from 5% per year to 17.5% - 25% per year for the probability of detecting the effect to exceed 75%.

These simulations must be considered preliminary because other potential factors that influence the precision of the model parameter estimates (and therefore the ability to detect an effect) are not considered. For example, the simulation assumes that the capture-recapture model is known, when in reality model uncertainty is incorporated in the estimation process (e.g., via model selection procedures). In addition, there was no variability added to the parameters of the simulation model. For example, capture probability and the proportion of tagged animals is constant across capture occasions. Adding variability would likely increase variance estimates of the model parameters and decrease power. Despite that, the simulations provide evidence that the power to detect a tag effect is small in tagging studies of false killer and short-finned pilot whales in Hawaiʻi because the tag effect for LIMPET tags is likely negligible, and because the number of tags deployed is low and variable across years.

IMPACT/APPLICATIONS

Understanding the potential for impacts of naval activities on protected species of marine mammals and mitigating such impacts requires information on movements and habitat use. The development of better tag technologies and deployment techniques will make a significant contribution to the ability of researchers to track movements, monitor behavior, and determine distribution of species of interest.

TRANSITIONS

Most parts of the LIMPET satellite tag and attachment system that we have developed and are improving in this project are commercially available from Wildlife Computers (Seattle, WA), and

LIMPET tags are being acquired by and deployed by multiple organizations (e.g. Southwest Fisheries Science Center, Cascadia Research Collective, Woods Hole Oceanographic Institution, among many others) in other projects funded by the US Navy to monitor marine mammals on Navy ranges and elsewhere.

RELATED PROJECTS

The National Marine Fisheries Service Pacific Islands Fisheries Science Center is supporting research on false killer whale movements in Hawaiian waters (Baird et al. 2010; 2012), and the Naval Postgraduate School (with funding from N45) is supporting tagging studies of a variety of species. Tag and deployment developments from this work are being incorporated into these ongoing studies. See:
www.cascadiaresearch.org/hawaii/beakedwhales.htm
www.cascadiaresearch.org/hawaii/falsekillerwhale.htm
www.cascadiaresearch.org/SCORE/SCOREMain.htm

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Figures

Fig. 1. CAD models of the most recent designs of the location-only LIMPET tag (AM-240C, Left) and the dive depth-transmitting LIMPET tag (AM-292, Right). The antennae and wet-dry sensors were removed to simplify the mesh

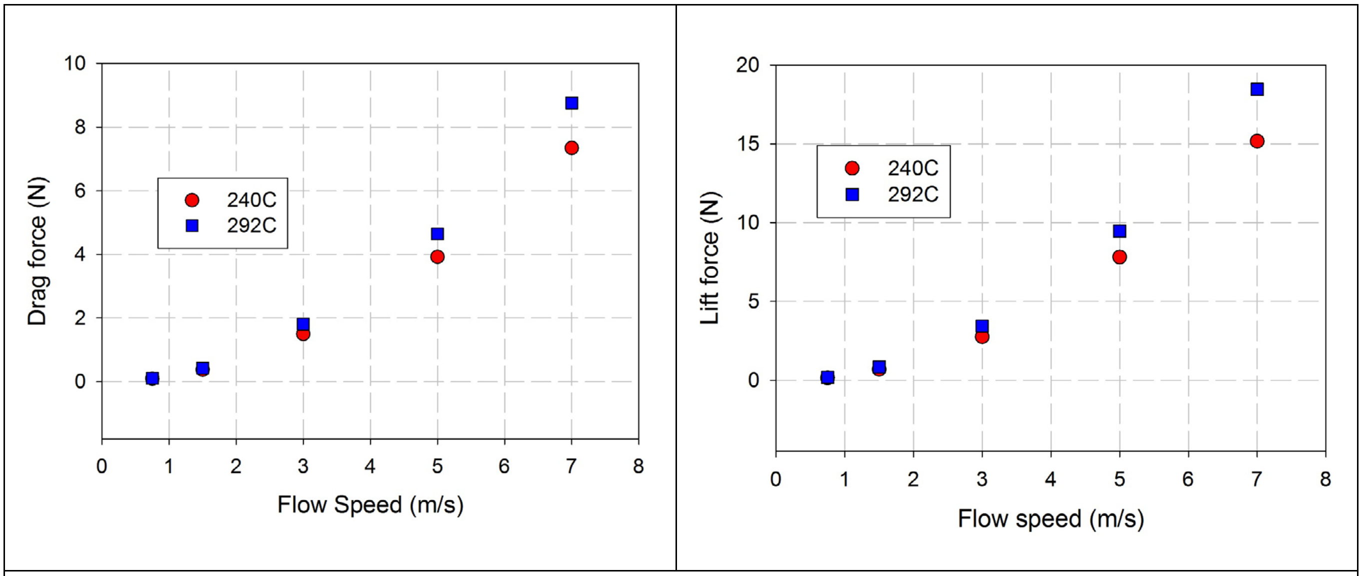

Fig. 2. Drag force (Left) and lift force (Right) vs. flow speed at 0 degree yaw and pitch angles for the AM-240C and AM-292C tags. The AM-292C tag generated slightly more drag and lift than the AM-240C tag, but it was only significant at higher speeds.

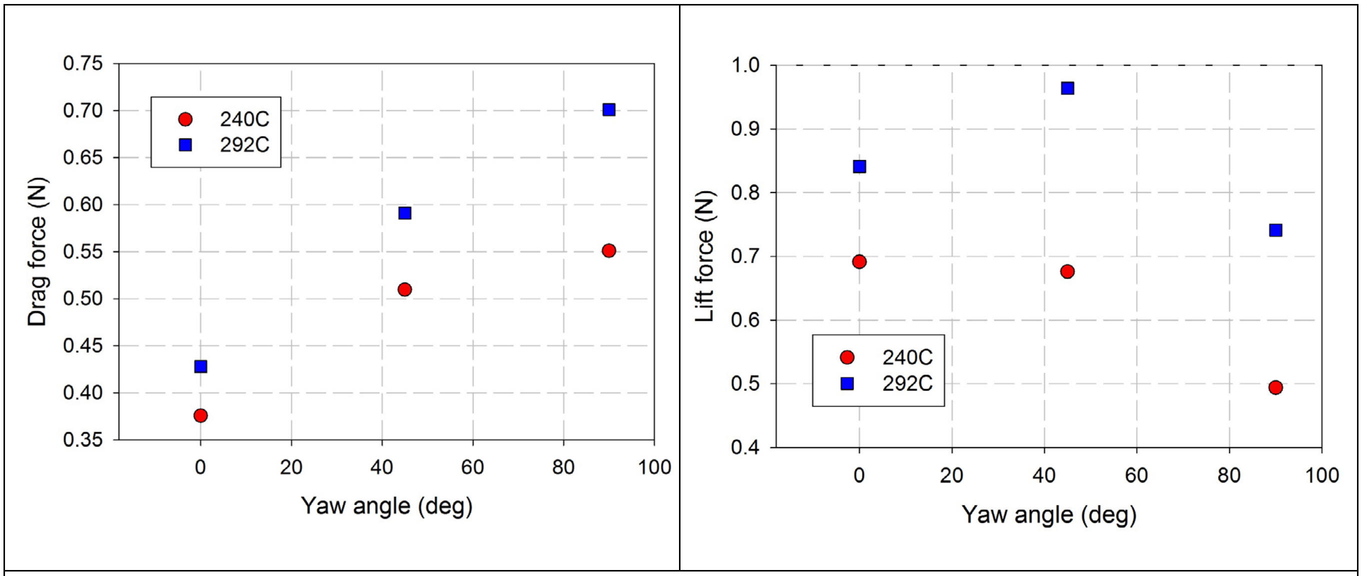

Fig. 3. Drag force (Left) and lift force (Right) at different yaw angles, at a fixed flow speed of 1.5 m/s.

Fig. 4. Pitch angles of 0° (left), 20° (center), and 40° (left). Flow direction: lower left to upper right.

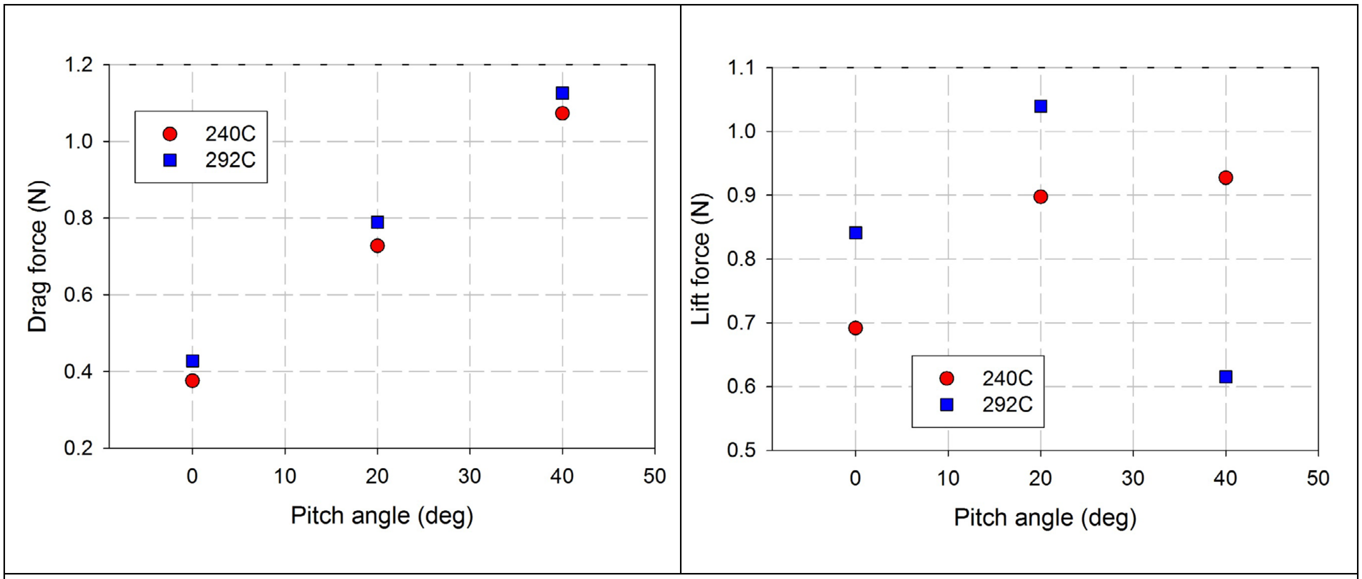

Fig. 5. Drag force (Left) and lift force (Right) at various pitch angles.

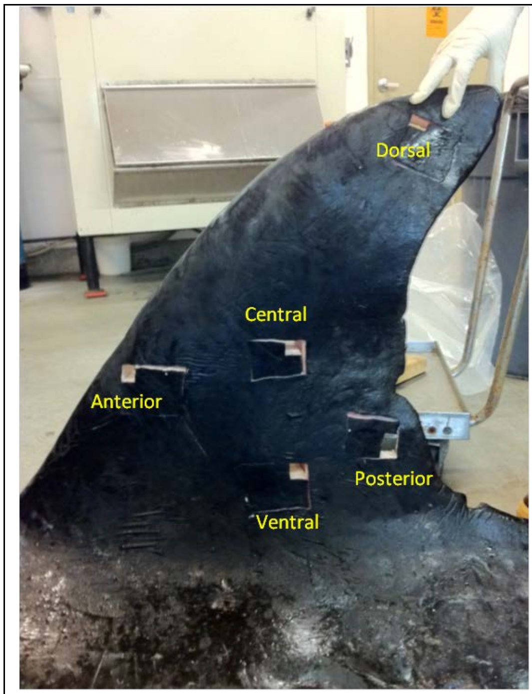

Fig. 6. Five regions of the killer whale dorsal fin where where we extracted samples to assess structural variability.

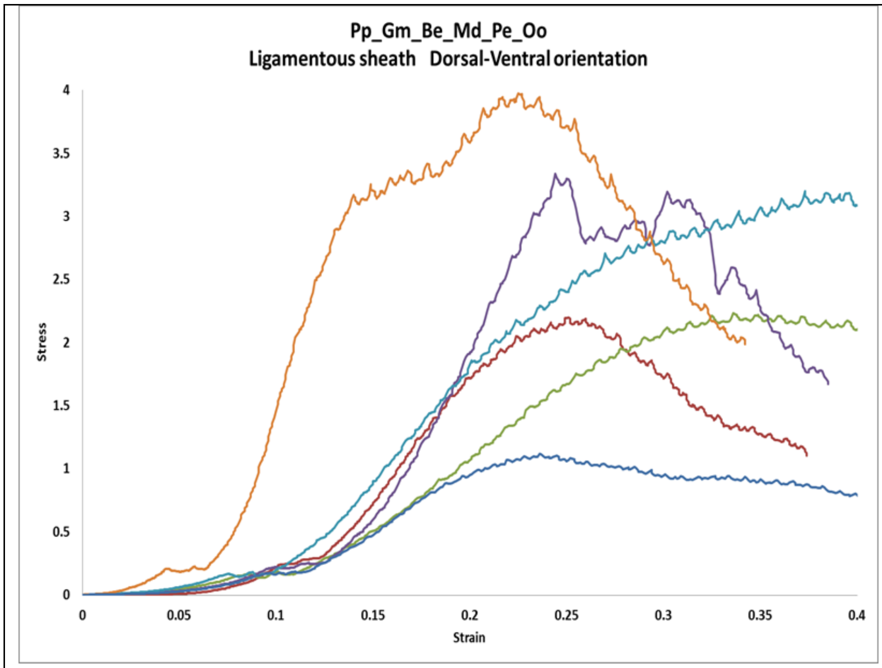

Fig. 7. Comparison of stress/strain curves for ligamentous sheath tissue layer of the dorsal fins in dorsal -ventral orientation for melon-headed (Pe), pilot (Gm), Bryde's (Be), killer (Oo), Cuvier's beaked (Zc), Blainville's beaked whales (Md), and harbor porpoise (Pp).

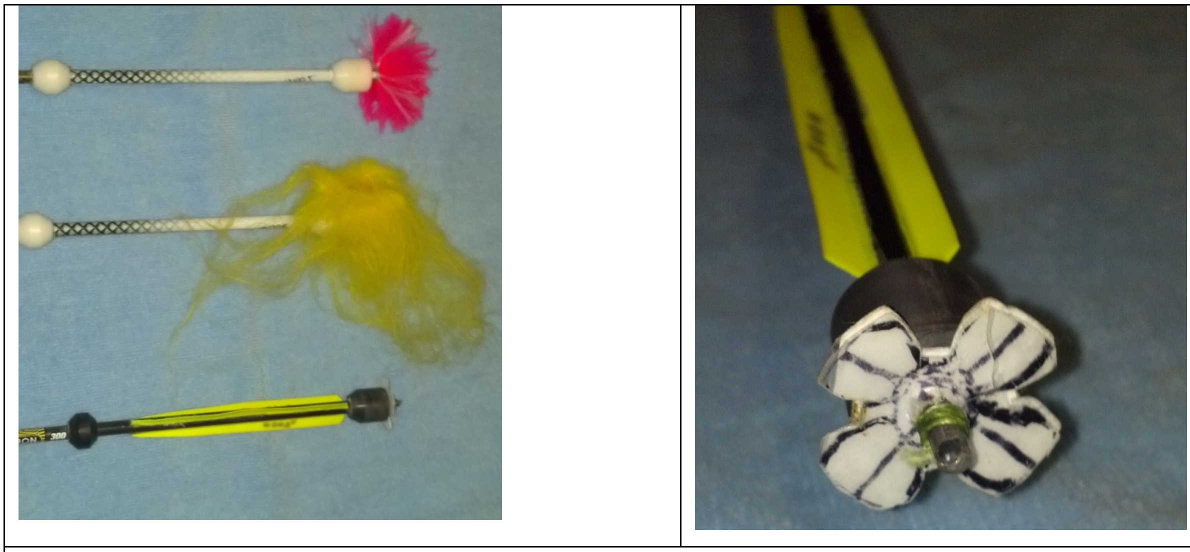

Fig. 8. Left: arrow end designs used in ballistics testing; from top to bottom; arrow m005, m006 and m007. Right:close up view of the end of arrow m007 showing the yellow vanes, similar to those found on crossbow bolts, and the addition of a plastic air brake that comes out proud of the end cap in flight.

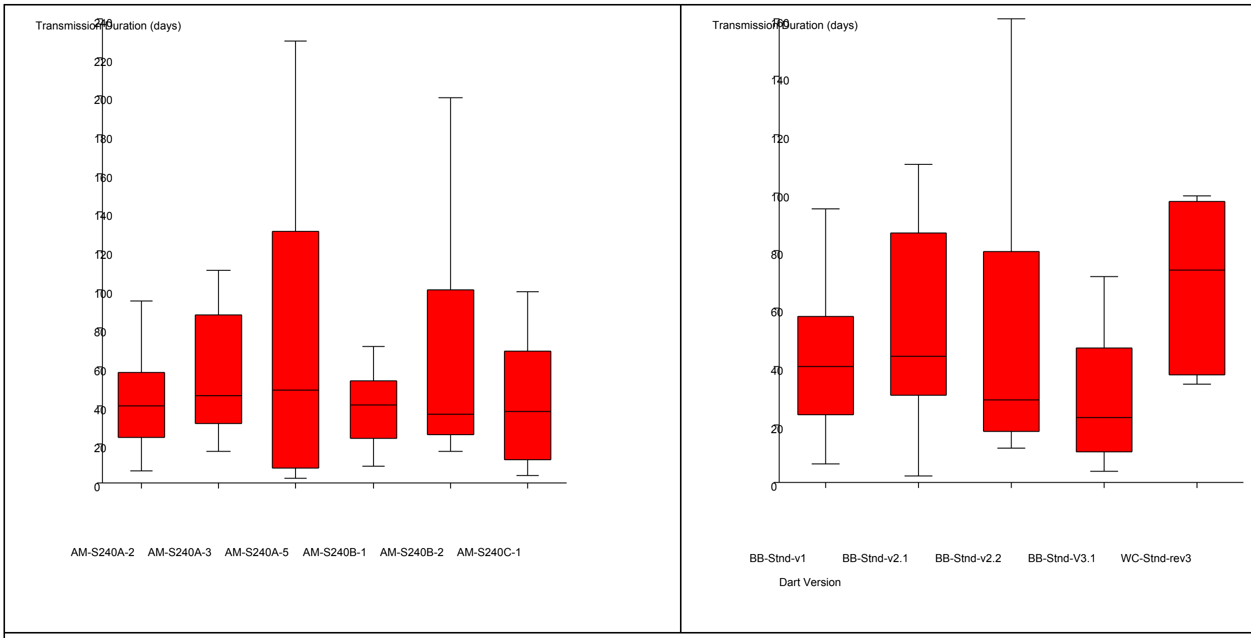

Fig. 9. Box plot (medians and inter-quartiles) of transmission duration by tag version (left) and dart version (right).

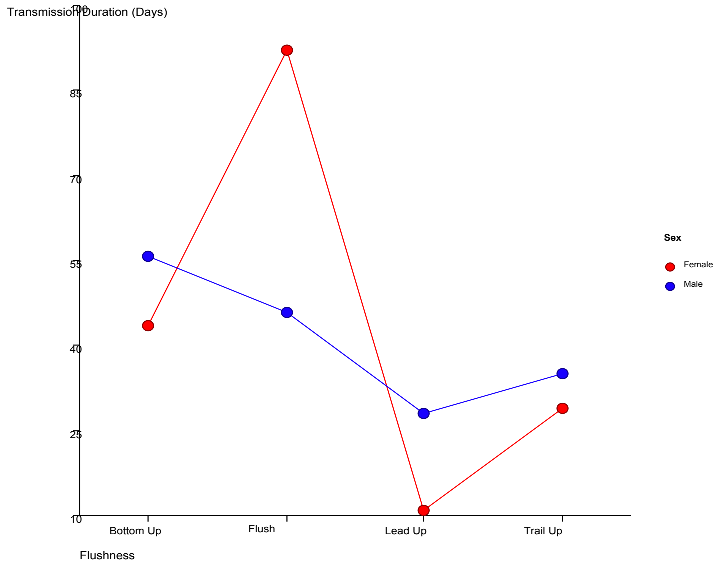

Fig. 10. Plot of transmission duration by degree of flushness and sex for FKW, SFPW, and KW