Advances in cetacean telemetry: A review of single-pin transmitter attachment techniques on small cetaceans and development of a new satellite-linked transmitter design

Article *in* Marine Mammal Science · August 2013

DOI: 10.1111/mms.12072

10 authors, including:

Brian Coleman Balmer
National Marine Mammal Foundation
67 PUBLICATIONS 1,214 CITATIONS

Randall Wells
Chicago Zoological Society
282 PUBLICATIONS 10,963 CITATIONS

Aaron A. Barleycorn
Mote Marine Laboratory
13 PUBLICATIONS 279 CITATIONS

Lori H Schwacke
National Marine Mammal Foundation
112 PUBLICATIONS 1,985 CITATIONS

Marine Mammal Science

MARINE MAMMAL SCIENCE, **(*): ***–*** (*** 2013)

DOI: 10.1111/mms.12072

Advances in cetacean telemetry: A review of single-pin transmitter attachment techniques on small cetaceans and development of a new satellite-linked transmitter design

BRIAN C. BALMER[1] and RANDALL S. WELLS, Chicago Zoological Society, ℅ Mote Marine Laboratory, 1600 Ken Thompson Parkway, Sarasota, Florida 34236, U.S.A.; LAURENS E. HOWLE, BelleQuant Engineering, PLLC, 7813 Dairy Ridge Road, Mebane, North Carolina 27302, U.S.A. and Department of Mechanical Engineering and Materials Science, Duke University, 144 Hudson Engineering Center, Durham, North Carolina 27708, U.S.A.; AARON A. BARLEYCORN, Chicago Zoological Society, ℅ Mote Marine Laboratory, 1600 Ken Thompson Parkway, Sarasota, Florida 34236, U.S.A.; WILLIAM A. MCCLELLAN and D. ANN PABST, Department of Biology and Marine Biology, University of North Carolina Wilmington, 601 South College Road, Wilmington, North Carolina 28403, U.S.A.; TERI K. ROWLES, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 1315 East-West Highway, Silver Spring, Maryland 20901, U.S.A.; LORI H. SCHWACKE, National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Hollings Marine Laboratory, 331 Fort Johnson Road, Charleston, South Carolina 29412, U.S.A.; FORREST I. TOWNSEND, Bayside Hospital for Animals, 251 Racetrack Road NE, Fort Walton Beach, Florida 32547, U.S.A.; ANDREW J. WESTGATE, Department of Biology and Marine Biology, University of North Carolina Wilmington, 601 South College Road, Wilmington, North Carolina 28403, U.S.A.; ERIC S. ZOLMAN, National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Hollings Marine Laboratory, 331 Fort Johnson Road, Charleston, South Carolina 29412, U.S.A.

Abstract

Electronic tags have proven to be valuable tools in assessing small cetacean movement and behavior. However, problems associated with tag size and attachment have limited duration and damaged dorsal fins. These outcomes have motivated researchers to develop a new satellite-linked tag design that reduces detrimental effects to tagged animals, while increasing transmission durations. The goals of this study were to review previous studies that deployed single-pin transmitters and determine factors that influence transmission duration. Then, test these factors utilizing computational fluid dynamics (CFD) models to identify an optimal single-pin satellite-linked tag design, and evaluate this prototype through field studies. A review of four projects, which deployed 77 single-pin radio tags, determined that tags attached along the lower third of the dorsal fin and approximately 33 mm from the trailing edge resulted in longer transmission durations and reduced negative impacts to the

[1]Corresponding author (e-mail: bbalmer@mote.org).

dorsal fin. Based upon these results and CFD modeling, prototype, single-pin satellite-linked tags (n = 25) transmitted for 163 ± 22 d (mean ± 95% CI) which greatly exceeded transmissions for previous small cetacean telemetry studies. These results suggest that the newly developed single-pin satellite-linked tag design strikes a balance between reducing impacts to the individual while maximizing transmissions.

Key words: bottlenose dolphin, computational fluid dynamics, telemetry, *Tursiops truncatus*.

Over the past four decades, telemetry has provided detailed information on small cetacean movement patterns, habitat use, and behavior that could not have been determined using other research techniques (*e.g.,* Evans 1971, Norris and Dohl 1980, Irvine *et al.* 1981, Read and Westgate 1997, Corkeron and Martin 2004). As technology improves and additional sensors are added to tags, the potential utility of telemetry data has continued to increase. Among the limiting factors in this progression have been tag and battery size, and the ability to safely and effectively attach transmitters to the dorsal fins of small cetaceans for sufficient time to collect meaningful data. Until recently, electronic tags were so large that they required multiple pins to be secured to the dorsal fin (*e.g.,* Mate *et al.* 1995, Klatsky *et al.* 2007). Migration of the attachment pin through the fin has led to fin damage and premature loss of transmitters before the batteries were exhausted (Irvine *et al.* 1982, Scott *et al.* 1990, Balmer *et al.* 2010).

A series of workshops have convened to examine the issue of electronic tag attachment (ONR 1992, 2009; Wells 2005). All have recommended systematic studies of factors influencing tag attachment success, and an assessment of tag designs, including laboratory and field testing. To date, in the absence of large scale systematic studies, researchers have worked independently with tag manufacturers to modify features believed to affect attachment, including tag size, shape, and configuration; number of attachment pins; pin size; and construction of tags. Some *ad hoc* opportunistic field tests have been possible under circumstances where tagged dolphins could be safely captured and handled, and were likely to be observed repeatedly postrelease or where tagged dolphins were recaptured and evaluated (Irvine *et al.* 1982; Mate *et al.* 1995; Read *et al.* 1997; Scott *et al.* 2005; Balmer *et al.* 2008, 2013; Scott and Chivers 2009). In other cases, when tagged individuals were not able to be directly observed, animal and tag condition were inferred from transmission features (Read and Westgate 1997; Westgate and Read 1998; Wells *et al.* 1999, 2008, 2009; Scott *et al.* 2001; Balmer *et al.* 2010). While these efforts have been informative, they have all been done on an opportunistic basis, usually involving small sample sizes. A larger and more systematic approach is necessary to comprehensively develop safe and effective tag and attachment designs.

Bottlenose dolphin (*Tursiops truncatus)* telemetry studies have been ongoing since 1970 (Irvine and Wells 1972). The results of these studies have suggested that optimal tag design is a compromise between minimizing the risk of injury to the animal, due to factors such as drag, mass, and thermoregulatory effects, while maximizing signal strength, range, and longevity of deployment (Scott *et al.* 1990, 2005), with the overriding consideration focusing on the well-being of the animal and not disrupting natural behavior. Irvine *et al.* (1982) documented some of the first dorsal fin radio tag attachment experiments on bottlenose dolphins in Sarasota Bay, Florida, using high frequency (HF) radio transmitters housed in one or two large tubes attached to a heavy fiberglass saddle that wrapped around the dorsal fin (Fig. 1A). The HF transmitters offered longer transmission distances, but at a cost of large tag size. Although successful in determining short-term movements of dolphins, many of these tags caused long-term dorsal fin damage (Gaskin *et al.* 1975, Irvine *et al.* 1982).

In 1993, Wells (RSW, unpublished data) developed a "roto-radio" tag system; newly available, small (14 g), very high frequency (VHF) radio transmitters were attached to the dorsal fin, via a cattle ear or roto tag (Wells 2009), which could be clipped through its trailing edge (Fig. 1B). This tag system was tested on bottlenose dolphins in Sarasota Bay and at a field site in Beaufort, North Carolina, with encouraging results (*e.g.*, Waples 1995, Read *et al.* 1996). The most recent iteration, the bullet radio tag (Trac Pac, Ft. Walton Beach, FL), encloses a 16 g VHF radio transmitter (MM130, Backmount transmitter, Advanced Telemetry Systems, Inc., Isanti, MN), with an estimated battery life of 74 d, in a modified orthopedic plastic casing. These tags are attached to the dorsal fin using a single hole and a 1/4″ acetal (acetal homopolymer; Delrin, DuPont Wilmington, DE) pin, with nonstainless steel (corrodible) hex nuts and stainless steel washers on each side of the dorsal fin (Fig. 1C).

More than 100 single-pin VHF radio transmitters and their improved successors have been deployed since 1992 for various research projects and postrelease monitoring of rehabilitated cetaceans (*e.g.,* Wells *et al.* 1998, in press; Owen 2003; Balmer *et al.* 2008, 2013). The general tag design features of the single-pin attachment positioned along the trailing edge of the dorsal fin were based upon the following assumptions:

(1) Minimal blood vessel and dorsal fin damage if tag migration occurred.
(2) Hydrodynamically more favorable as opposed to tags attached along the side or front of the dorsal fin.
(3) Ease of attachment (*i.e.,* no complex templates for drilling holes into dorsal fin).
(4) Thermal considerations (*i.e.,* tag does not cover large surface area of dorsal fin).

The small size of these tags minimized drag, fin damage, and thermoregulation effects, while the short reception ranges (<8 km) and tag duration (<3 mo) were determined to be acceptable tradeoffs for the inshore tracking studies being conducted.

Although VHF radio telemetry has proven successful at determining movement patterns of tagged individuals (*e.g.,* Irvine *et al.* 1982, Balmer *et al.* 2008), the technique can be expensive, labor intensive, limited by weather and sea state, and it offers only limited geographic coverage (reviewed in Balmer *et al.*, in press). Satellite-linked radio telemetry provides location data and other behavioral information on tagged animals *via* a satellite-based data collection system, which far exceeds the capabilities of VHF radio tracking (Cooke *et al.* 2004). Satellite-linked transmissions are detected and analyzed through the Argos Data Collection and Location System (Argos DCLS), which consists of a series of satellites orbiting the earth. If two or more transmissions are received by a satellite during a single orbit, then a location is determined from Doppler shift of repeated transmissions (reviewed in Eckert and Stewart 2001). Location quality is dependent on the number of transmissions during a satellite pass, time between signals, position of the satellite tag on the animal, and stability of the transmitter oscillator (Westgate *et al.* 1999). The highest location quality data (Class 3) have greater than five transmission uplinks received in one satellite

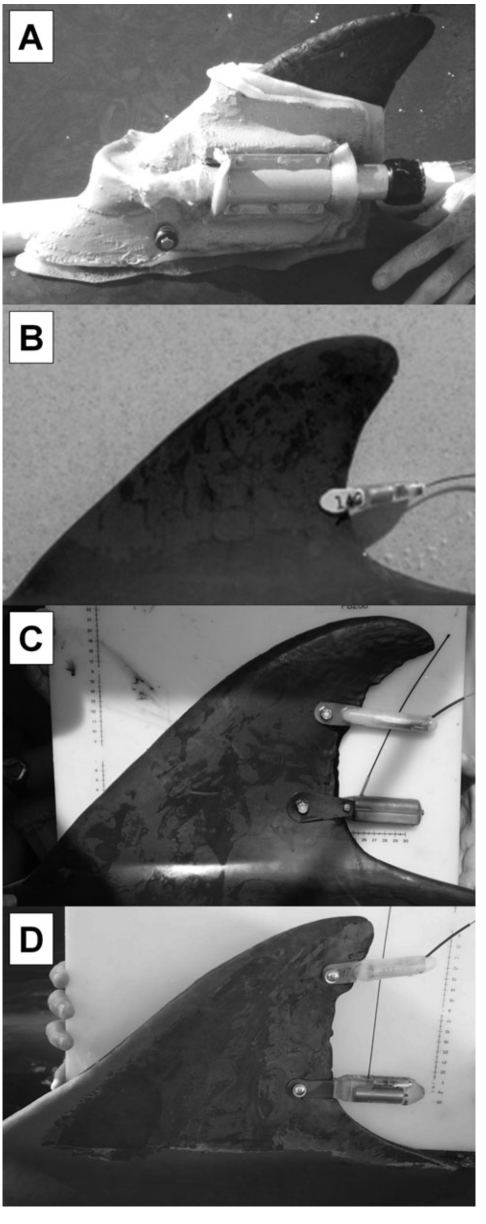

Figure 1. Examples of single-pin transmitter attachment designs: (A) HF radio transmitter housed in tube/saddle (Irvine *et al.* 1982); (B) VHF roto-radio tag (1993); (C) VHF bullet radio tag (upper) and single-pin satellite-linked tag (SirTrack, Kiwisat 202 Cetacean Fin Tag model K2F161) (lower) with 1/4″ acetal pin and nonstainless steel (corrodible) 1/4″ × 20 hex nuts (2009); and (D) VHF bullet radio tag (upper) and single-pin satellite linked tag (Wildlife Computers, SPOT-100, Single Point Finmount satellite-linked transmitter) (lower) with 5/16″ acetal pin and zinc-plated steel, 10-14 × 3/8″ pan head thread-cutting screws (2011).

pass, and a position accuracy of approximately 150 m (reviewed in Balmer *et al.* 2010). However, problems related to transmitter size, location on the dorsal fin, and the number of attachment pins have, in some cases, shortened the predicted attachment duration and caused damage to the dorsal fins (Scott *et al.* 1990, Read *et al.* 1997, Balmer *et al.* 2010). These failures motivated the development of a smaller satellite-linked transmitter with an attachment design comparable to that of the single-pin bullet radio tag, with the goals of minimizing negative impacts to the dorsal fin while maximizing transmitter longevity.

Recently, a satellite-linked transmitter that was of a suitable size to be attached *via* a single-pin has been developed. Working with dolphin researchers during the summer of 2009, SirTrack (Havelock North, New Zealand) manufactured a prototype, 37 g, location-only, satellite-linked transmitter (PTT) that was designed to be attached to the trailing edge of the dorsal fin using a single acetal pin (1/4″), held by nonstainless steel (corrodible) 1/4″ × 20 hex nuts and stainless steel washers (Kiwisat 202 Cetacean Fin Tag model K2F161) (Fig. 1C). During a bottlenose dolphin health assessment project in Georgia, three of these transmitters were deployed and monitored for more than three months to assess animal and tag condition (Balmer *et al.* 2011*a*). The results from this study suggested that this new single-pin attachment design was a significant improvement over previous multi-pin designs, with location data comparable to previous studies and minimal dorsal fin damage. However, all three of these satellite-linked tags had different modes of failure: acetal pin or corrodible nut, pin migration, and battery failure. Additional research, and a larger sample size, is necessary to provide a quantitative analysis of factors influencing tag retention and transmission duration based upon laboratory testing and field studies.

The goals of this study were to identify an optimal single-pin tag design and attachment location on dolphin dorsal fins. This involved an evaluation of previous deployments of single-pin tags, computational fluid dynamics (CFD) simulations, and then field deployment and monitoring of the modified satellite-linked tags. Data on bullet VHF radio tag performance from four prior bottlenose dolphin health assessments in the southeastern U.S. were used to identify factors that influence tag retention, transmission duration, and effects on the tagged individual. Hydrodynamic drag tests were performed on a recent single-pin satellite-linked tag design (Balmer *et al.* 2011*a*) and CFD studies were used to measure the drag on a variety of tag designs placed at multiple positions along the trailing edge of the dorsal fin. Prototype, satellite-linked transmitters, based upon the CFD models, were deployed and subsequently monitored for the life of the tags on bottlenose dolphins in Barataria Bay, Louisiana.

Methods

Single-pin Tag Review

To identify differences in tag design and attachment success, telemetry data were reviewed from 77 bullet VHF radio tags deployed during bottlenose dolphin health assessments in St. Joseph Bay, Florida (2005 and 2006) (Balmer *et al.* 2008), southern Georgia (2009) (Balmer *et al.* 2011*a*, *b*, 2013, in press), and Barataria Bay, Louisiana (2011). The following factors were examined to assess tag retention, transmission duration, and dorsal fin condition from the bullet VHF radio tags.

Minimum number of days tag transmitted—The total number of days from tag attachment until the last day the animal was sighted with a transmitting tag (the tag may have continued to transmit after this last sighting).

Distance from trailing edge to attachment hole—Shortest measurement from the middle of the attachment hole to the trailing edge of the dorsal fin (mm).

Tag location on dorsal fin—Vertical location of tag attachment along the trailing edge of the dorsal fin: (1) *High*, upper third of trailing edge; (2) *Middle*, middle third of trailing edge; (3) *Low*, lower third of trailing edge.

Type of attachment—Attachment used to secure tag to dorsal fin; 1/4″ × 20 hex nuts with 1/4″ acetal pin, or 10-14 × 3/8″ pan head thread-cutting screws with 5/16″ acetal pin.

Biogrowth—Amount of fouling that developed on the tag during follow-up monitoring within the estimated battery life of the tag: (1) *Heavy*, biogrowth covering >75% of tag; (2) *Moderate*, biogrowth covering 25%–75% of tag; (3) *Slight*, biogrowth covering <25% of tag; (4) *Unknown*, animal not resighted with tag.

Mode of tag failure—Hypothesized reason for the tag no longer transmitting: (1) *Battery*, tag was sighted, intact on dolphin, no longer transmitting, and battery voltage was <3.00V and/or the cumulative number of transmissions were >40,000; (2) *Acetal pin/corrodible nut*, dolphin was sighted without tag prior to end of estimated battery life and a hole was observed at the attachment location; (3) *Migration*, dolphin was sighted without tag prior to the end of estimated battery life and a notch was observed extending from the attachment location to the trailing edge of the dorsal fin; (4) *Unknown*, animal was not resighted within the estimated battery life with the tag attached and no longer transmitting, or without tag.

Condition of dorsal fin posttag loss—Damage caused by the tag attachment: (1) *Hole*, well-healed hole at the attachment location; (2) *Notch*, well-healed notch from the attachment location to the trailing edge of the dorsal fin; (3) *Unknown*, dolphin was not resighted without its tag.

Analyses of variance (ANOVA) tests were performed to assess which factors influenced tag transmission (tag location on dorsal fin, biogrowth, and type of attachment), with the minimum number of days each tag transmitted as the response variable. Additional ANOVAs were performed to determine if distance from the trailing edge of the dorsal fin to the attachment hole was correlated with the mode of tag failure and condition of dorsal fin posttag loss. When the F-statistic was significant ($P < 0.05$ or $\alpha = 0.05$), pairwise comparisons were made using Tukey's Honestly Significant Difference (HSD) test.

Computational Fluid Dynamics

Computational fluid dynamics (CFD) studies of distance from trailing edge to attachment hole, antenna position on the tag, and attachment location on the dorsal fin were conducted using SolidWorks Flow Simulation 2012 (SolidWorks 2012) on an 8-core, 32 GB RAM workstation. The goal of these simulations was to identify tag configurations and attachments that reduce the hydrodynamic drag. A computational domain containing an idealized dorsal fin was used for all CFD studies. A grid convergence study was performed with mesh densities ranging from 632,000 to 3,070,000 finite volume cells. This study determined that a mesh with an approximate density of 632,000 cells gave a reasonable combination of solution accuracy and computation time. Therefore, this mesh density was used for all of the CFD studies with the exception of the tag location study, where approximately 1,658,000 finite volume cells were used. This allowed a single local mesh refinement region for all of the tag location configurations.

The inflow and outflow boundary conditions on the computational domain consisted, respectively, of uniform velocity and fixed static pressure. No-slip (viscous) boundary conditions were used on the dorsal fin and tag surfaces while free-slip (inviscid) boundary conditions were used on the top, bottom, and side walls of the computational domain. The k-ε Reynolds averaged Navier-Stokes turbulence model simulations were run in parallel using all eight cores of the workstation with a mean computing time for each simulation of approximately 180 min (Weber *et al.* 2011). All of the CFD simulations considered in this work used a free stream flow speed of 2.058 m/s (4.0 kn).

Prototype Single-pin Satellite-linked Tag Assessment

In August 2011, a health assessment of bottlenose dolphins was conducted in Barataria Bay, Louisiana, as part of the Natural Resource Damage Assessment (NRDA) conducted by NOAA, other federal and state Trustees, and their partners in response to the 2010 Deepwater Horizon Oil Spill. Dolphins were captured, examined, tagged, and released using practices similar to those established for health assessments of bottlenose dolphins in Sarasota Bay, Florida (Wells *et al.* 2004). Twenty-five dolphins were tagged with a 54 g, location-only, SPOT-100, Single Point Finmount satellite-linked transmitter (Wildlife Computers, Redmond, WA), the design of which was based upon the findings from the CFD models for reducing drag (Fig. 1D).

Based upon the attachment location results from previous studies and the CFD modeling, the satellite-linked tag was placed along the lower third of the trailing edge, and the center of the hole in the attachment wing was marked with a permanent marker at a distance of approximately 38 mm from the trailing edge. Wearing surgical gloves, the researcher attaching the tag cleaned the attachment site with a Dermachlor (Chlorhexidine 2%) (Butler Schein Animal Health, Inc., Dublin, OH) scrub followed by methanol. Using a Miltex N-Tralig intraligamentary syringe (Integra LifeSciences Corporation, Plainsboro, NJ), 1–2 ml of lidocaine hydrochloride and epinephrine (1:100,000) (Cook-Waite, Carestream Health, Inc., Cambridge, Ontario, Canada) was injected directly into the center of the attachment location mark on the dorsal fin, with three injections of the same volume surrounding this site as well. A sterilized stainless steel 5/16″ coring tool was centered over the attachment location mark, and pushed by hand through the fin into a rubber sanding block held against the fin on the other side. The core was saved for genetic analyses in a vial of DMSO stored at room temperature. An acetal pin of appropriate length (approximately 20 mm), soaked in Dermacholor prior to attachment, was inserted through the hole in the dorsal fin. The wings of the tag were placed over the holes in the pins, and two zinc-plated steel, 10-14 × 3/8″ pan head thread-cutting screws with two 1/4″ stainless steel, small flat washers were attached by hand-tightening with screw drivers, to the point where approximately 1 mm of space remained between each wing and the fin. The tag was tested for function, photos were taken of the attachments and dorsal fin, and the animal was ready for release.

The satellite-linked tags were programmed to optimize battery life and access to satellites. They were set to transmit during two four-hour windows each day (0200–0559 and 0800–1159 CST), based on ARGOS satellite pass prediction values, looking for satellites with >20° elevation for at least 3 min. The tags were programmed to transmit up to 250 times each day, yielding a theoretical maximum of up to 240 tracking days based upon battery life. Of the 25 dolphins tagged with satellite-linked transmitters, 21 also received a bullet VHF radio tag (Fig. 1C) attached to the upper third of their fin for small-vessel based, direct radio-tracking and visual follow-up of animal and tag condition. Five additional dolphins received only a bullet radio tag attached at the same position as the satellite-linked tags. Follow-up monitoring of animal and tag condition, and additional photo-identification surveys were conducted by the Louisiana Department of Wildlife and Fisheries, the Chicago Zoological Society, and NOAA.

To assess satellite-linked tag condition, the same factors were used as those for the bullet VHF radio tags, excluding distance from trailing edge to attachment hole, tag location on the dorsal fin, pin diameter, and type of attachment, which were the same across all satellite-linked tag attachments: 38.6 mm, low, 5/16″, and 10-14 × 3/8″ pan head thread-cutting screws, respectively. Satellite-linked tags can be monitored remotely for the duration of the tag's life, thus, the number of days from attachment to final transmission was calculated as opposed to the minimum number of days the tag transmitted from the direct radio tracking. ANOVAs were performed to investigate the relationships between the number of days from attachment to final transmission (response variable), modes of tag failure, tag transmission rates, and biogrowth.

Results

Single-pin Tag Review

The mean number of days that the single-pin radio tags (n = 77) transmitted during the four projects investigated in this study was 49 (95% CI: 42–56 d). Radio tags attached along the lower third of the dorsal fin had a significantly higher number of transmission days (56 ± 12 d; mean ± 95% CI) than tags attached along the upper third of the dorsal fin (38 ± 7 d) (P = 0.0305) (Fig. 2A). The number of transmission days was significantly higher for tags with 1/4″ × 20 hex nuts and 1/4″ pins (57 ± 9 d) than 10-14 × 3/8″ pan head thread-cutting screws with 5/16″ pins (39 ± 6 d) (P = 0.0019) (Fig. 2B). Radio tags with heavy biogrowth transmitted significantly longer (76 ± 21 d) than tags with slight biogrowth (45 ± 7 d) (P = 0.0050) (Fig. 2C).

The distance from trailing edge to attachment hole was significantly correlated with mode of tag failure (P = 0.0293) and condition of dorsal fin posttag loss (P = 0.0006) (Fig. 3). Radio tags that were attached deeper into the dorsal fin failed predominantly due to battery life and left a hole in the fin, while tags attached closer to the trailing edge tended to fail by migration and left a notch.

Computational Fluid Dynamics

The first CFD study examined distance from trailing edge to attachment hole, defined as the distance between the junction of the left and right tabs and the centerline of the attachment fastener hole (Fig. 4A). Three distances were considered: 25 mm, 35 mm, and 38.6 mm. The greatest difference in hydrodynamic drag was found to be 1.2%. Therefore, distance from trailing edge to attachment hole was considered an insignificant driver of overall drag. Based on the team's previous experience with single-pin tracking tags, the 38.6 mm distance was

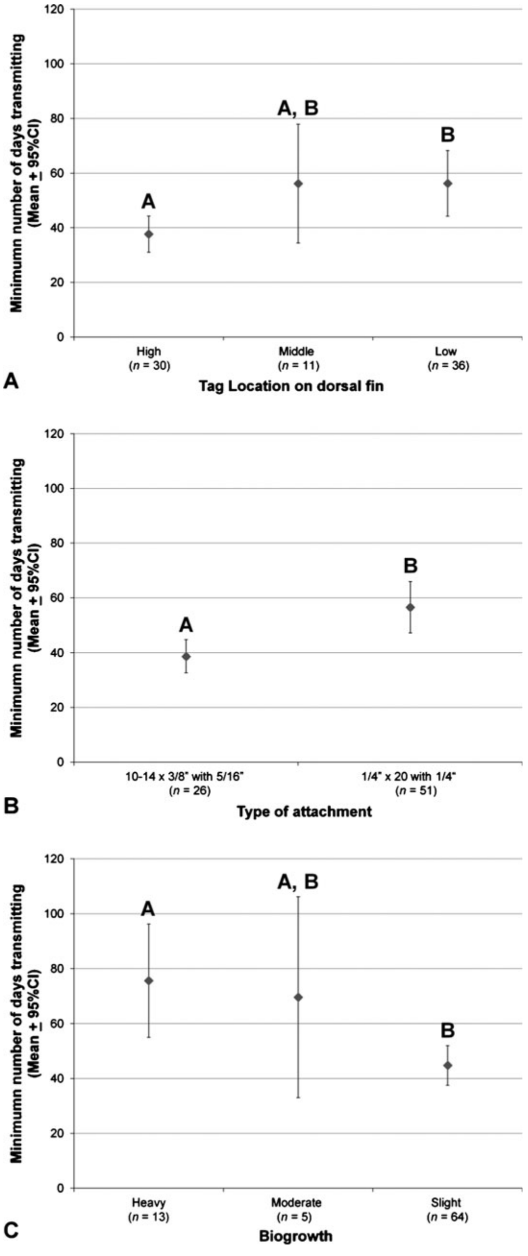

Figure 2. Minimum number of days bullet radio tags transmitted (mean ± 95% CI) grouped by (A) tag location on the dorsal fin, (B) type of attachment, and (C) biogrowth.
Note: Statistical differences were determined utilizing one-way ANOVAs. When the *F*-statistic was significant, pairwise comparisons were made using Tukey's Honestly Significant Difference (HSD) test. Points that share the same letter are not significantly different from each other.

selected to increase the distance between the dorsal fin trailing edge and the attachment acetal pin, as well as to increase the dorsal fin thickness at the point of attachment.

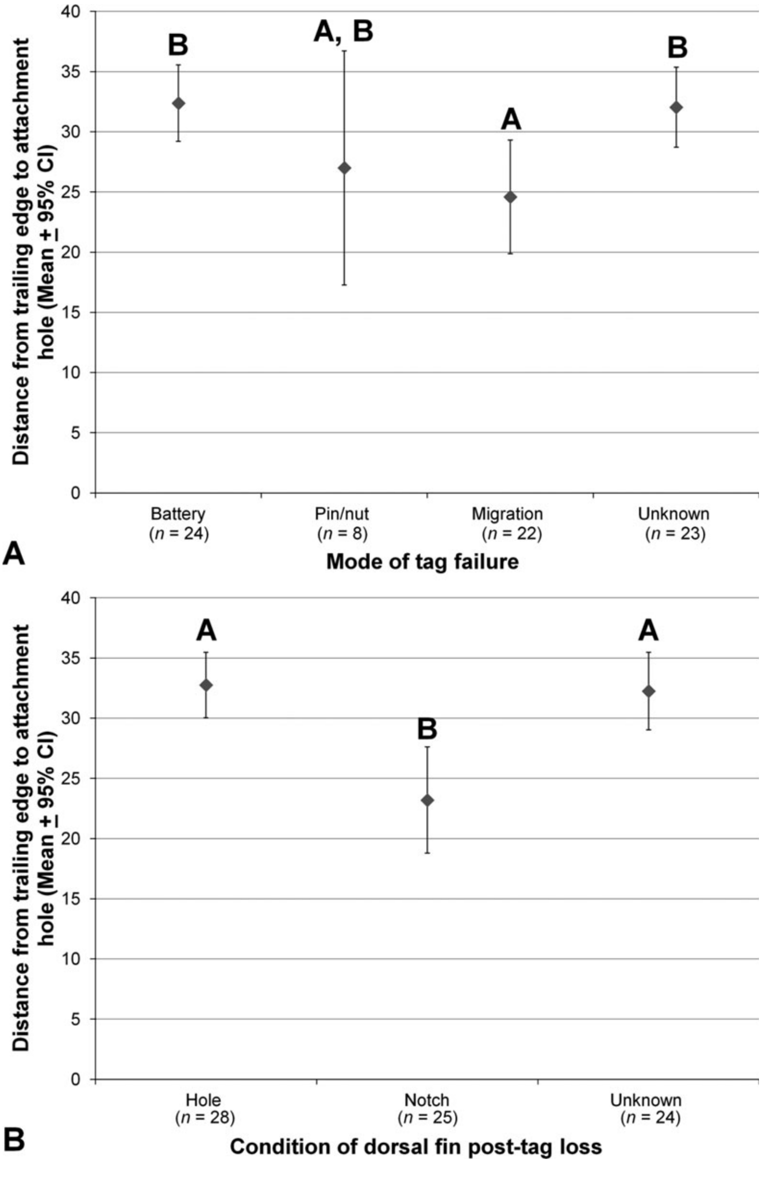

Figure 3. Tag attachment distance (mm) from trailing edge to attachment hole (mean ± 95% CI) grouped by (A) mode of tag failure and (B) condition of dorsal fin posttag loss.
Note: Statistical differences were determined utilizing one-way ANOVAs. When the *F*-statistic was significant, pairwise comparisons were made using Tukey's Honestly Significant Difference (HSD) test. Points that share the same letter are not significantly different from each other.

The influence of antenna mounting position on the hydrodynamic drag was examined at three positions: fore, mid, and aft (Fig. 4B). The mid and aft antenna mounting position, when compared to the forward antenna mounting position, resulted in drag increases of 6% and 15%, respectively. Therefore, the forward antenna mounting location was selected for the new satellite-linked tag design.

The hydrodynamic drag effect of the location of the satellite tag on the dorsal fin was another design variable examined. A reference vertical position, which was the perpendicular distance from the attachment screw center to a horizontal line at the level of the cranial insertion of the dorsal fin, was specified. Then, the vertical distance between this point and the satellite tag mounting pin centerline was varied from 50 to 200 mm with increments of 25 mm (Fig. 5). All of the CFD simulations were conducted with a 2.058 m/s (4.0 kn) free-stream flow speed. The 04 position (100 mm from the anterior insertion of the dorsal fin) incurred the least hydrodynamic drag. The 09 position had the greatest amount of drag relative to the 04 position (120%).

Prototype Single-pin Satellite-linked Tag Assessment

The mean number of days from attachment to final transmission for the 25 satellite-linked tags was 163 (95% CI: 141–185 d). Of the 25 tagged individuals, 84% (n = 21) had a hole posttag loss, 4% (n = 1) had a notch, and 12% (n = 3) were unknown. The mode of satellite-linked tag failure was significantly correlated with the number of days a tag transmitted ($P < 0.0001$) (Fig. 6A). The single tag that migrated out of the fin transmitted for the lowest number of days (54). The tags that detached by the corroding of the pin transmitted for 145 ± 20 d (mean ± 95% CI), while the tags that suffered battery failure transmitted for 211 ± 27 d. There was no relationship between biogrowth and the number of days from attachment to final transmission ($P = 0.1342$) (Fig. 6B).

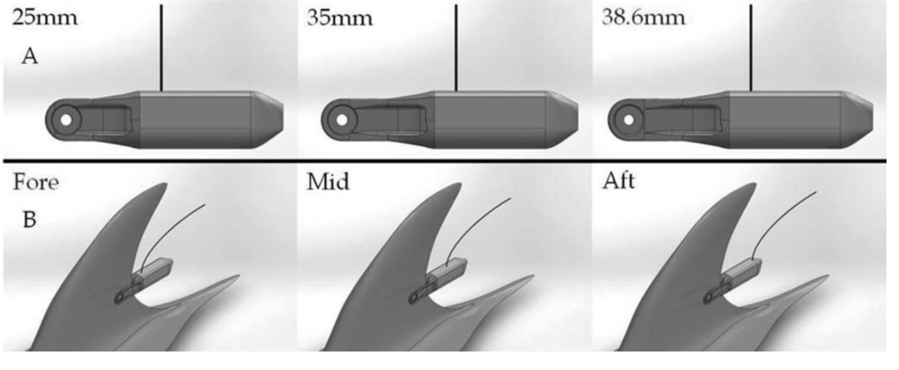

Figure 4. Illustrations of tag configurations during computational fluid dynamics (CFD) studies of (A) tab length and (B) antenna position. For the tab length study, attachment tab length (distance from the internal junction of the left and right tabs to the attachment screw center) was tested for lengths of 25.0 mm, 35.0 mm, and 38.5 mm. No significant difference in drag was found. The antenna position study used fore, mid, and aft antenna locations. The mid and aft locations gave increases in drag over the fore location of 6.0% and 15%, respectively.

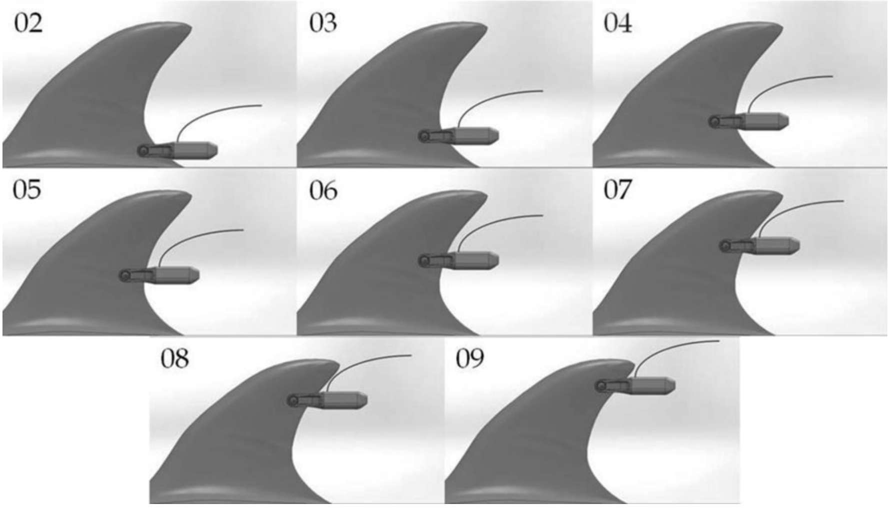

Figure 5. Illustrations of tag placement during computational fluid dynamics (CFD) studies. The vertical perpendicular distance from the attachment screw center to a horizontal line at the level of the cranial insertion of the dorsal fin is shown for each location. The 04 position (upper right image) incurred the least drag. Position 09 had the greatest drag with an increase of 120% over position 04.

Discussion

This study presents quantitative data that provides insight into the design, attachment, and performance of single-pin VHF and satellite-linked tags, with the goal of an appropriate balance between minimizing impacts to the tagged individual, and maximizing tag transmissions. VHF radio tags attached along the lower third of the dorsal fin and approximately 33 mm from the trailing edge resulted in higher transmission durations and lower impacts to the dorsal fin, resulting in a fully healed hole rather than a notch from tag migration (Fig. 2, 3). These results were supported by those of the Barataria Bay satellite-linked telemetry study, in which all tags were attached along the lower third of the dorsal fin, at an attachment distance of 38.6 mm from the trailing edge. Of the 22 satellite-linked tags for which the mode of tag failure could be identified, only one tag migrated through the dorsal fin, and the mean tag transmission duration was 163 ± 22 d (mean ± 95% CI) (Fig. 6). These tag transmission durations exceeded those of previous small cetacean studies in which multi-pin, time-depth recording satellite-linked tags (n = 10, 28 ± 17 d; mean ± SD) (Klatsky *et al.* 2007; Wells *et al.* 2008, 2009; Balmer *et al.* 2010), and the single-pin, location-only, satellite-linked tags deployed along the Georgia coast (n = 3, 61 ± 9 d; mean ± SD) (Balmer *et al.* 2011*a*) were used.

As part of the redesign process, the hypothesis was tested that increasing the diameter of the attachment pin from 1/4″ to 5/16″ would spread the shearing force of the pin across more fin tissue, and reduce the possibility of the pin migrating through the fin. In addition, it was hypothesized that using pan head thread-cutting screws over hex nuts would reduce drag at the attachment location. However, the radio tags attached with 1/4″ × 20 hex nuts and 1/4″ pins transmitted significantly longer than

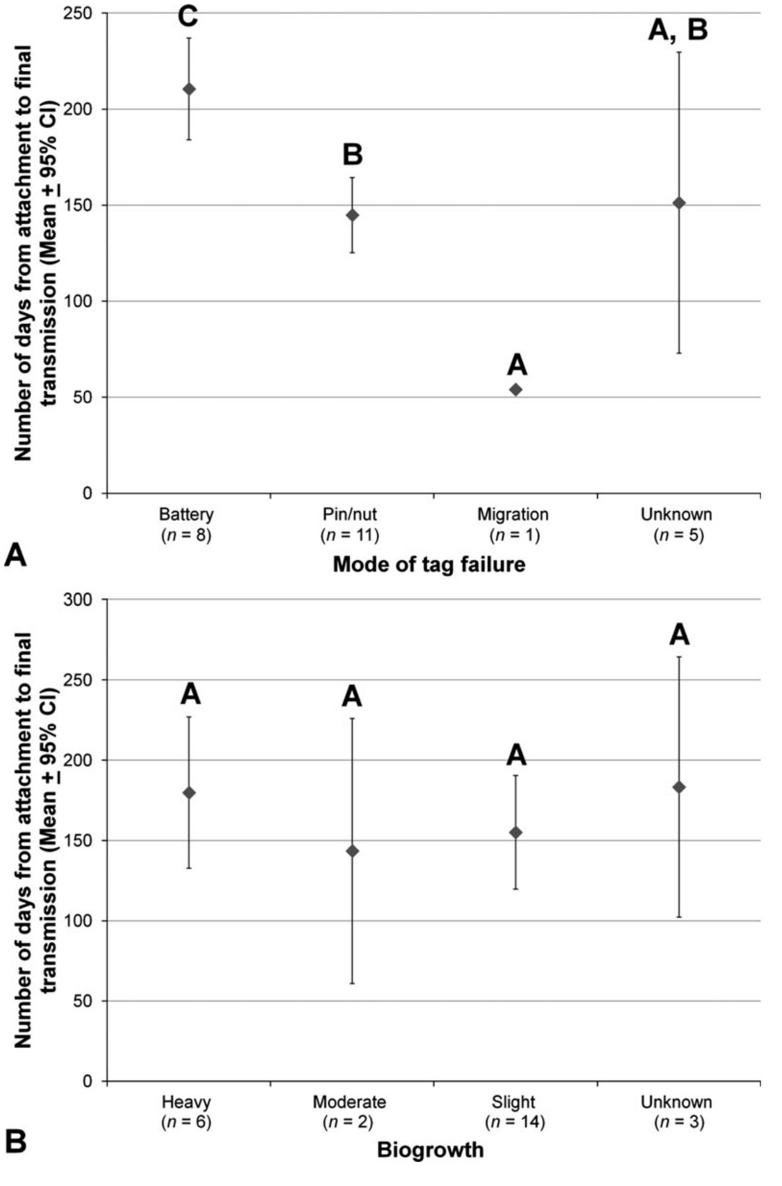

Figure 6. Number of days from satellite-linked tag attachment to final transmission grouped by (A) mode of tag failure and (B) biogrowth.
Note: Statistical differences were determined utilizing one-way ANOVAs. When the *F*-statistic was significant, pairwise comparisons were made using Tukey's Honestly Significant Difference (HSD) test. Points that share the same letter are not significantly different from each other.

those with 10-14 × 3/8″ pan-head thread-cutting screws and 5/16″ pins (Fig. 2B). The tag attachment location (high, middle, and low) was likely an additional factor that contributed to the differences observed in pin diameter and type of attachment.

Hex nuts with 1/4″ pins were used to attach radio tags at all three attachment locations in St. Joseph Bay and southern Georgia. However, all of the radio tags in Barataria Bay were attached using pan head thread-cutting screws and 5/16″ pins and the majority (21 of 26) were attached along the upper third of the fin, to permit follow-up radio tracking of dolphins also tagged with a satellite-linked transmitter. Based upon the results of the CFD simulations (Fig. 5) and radio tagging data (Fig. 2A), tags attached along the lower third of the fin had a higher number of days transmitting. Thus, determining the roles that pin diameter and type of attachment play in tag longevity requires further study.

Biogrowth was also hypothesized to contribute to tag transmission duration. Biogrowth could cover tag sensors or create additional drag on the dorsal fin, increasing the likelihood of tag failure. In addition, hard-bodied organisms, such as barnacles, which grow on the tag, may cause wounds along the peduncle or dorsal fin, creating sites for infection. However, radio tags that transmitted longer also experienced more biogrowth than those with shorter transmission durations (Fig. 2C), and there was no relationship between tag transmission durations and biogrowth for the satellite-linked tags (Fig. 6B). Although this study did not identify biogrowth as a significant factor influencing transmission duration, as attachment durations continue to increase thereby allowing for denser biogrowth, future research would be useful to investigate anti-fouling coatings that are, most critically, safe for the animal and successful in reducing or eliminating tag biogrowth.

This study identified an effective satellite-linked tag attachment type and dorsal fin location for bottlenose dolphins; 10-14 × 3/8″ pan head thread-cutting screws and 5/16″ pins attached along the lower-third of the dorsal fin at a distance of 38.6 mm. Although numerous studies have investigated the function (*e.g.,* Fish and Rohr 1999; Meagher *et al.* 2002, 2008; Westgate *et al.* 2007; Barbieri *et al.* 2010) and anatomy (*e.g.,* Scholander and Schevill 1955, Wainwright *et al.* 1982, Pabst *et al.* 1999) of the dorsal fin, quantitative data on dorsal fin morphology is scarce. Mechanical tests, similar to investigating epidermal effects of entangling lines on humpback (*Megaptera novaeangliae*) and North Atlantic right (*Eubalaena glacialis*) whales (Winn *et al.* 2008), would be useful in identifying effects associated with different sized attachments on the dorsal fins of different small cetacean species and age classes. Morphological analyses of small cetacean dorsal fins utilizing a macroscopic polarized light imaging system (Hamilton *et al.* 2004, Harper *et al*. 2008) to illuminate collagen fibers would provide a quantitative analysis of fiber orientation, size, and density, which could be used to identify an optimal tag attachment location.

The single-pin satellite-linked tags deployed in this study provided location-only data for bottlenose dolphins in and around Barataria Bay, Louisiana. Location-only tags are useful for identifying ranging patterns of coastal and estuarine cetacean species; however, time-depth recorders can provide additional insight into animal behavior (*e.g.,* Klatsky *et al.* 2007, Wells *et al.* 2009). Development of a single-pin, satellite-linked, time-depth recorder (TDR) tag with a design similar to that of the location-only tag used in this study would enable researchers to use a versatile tag to address a broad spectrum of research goals. In addition, visual observations of a tagged individual are crucial to assessing animal and tag condition. Development of a single tag that has both satellite-linked and VHF radio transmitters or a satellite-linked transmitter that can be efficiently tracked using a PTT locator would permit researchers to perform follow-up monitoring of animal and tag condition without the attachment of two separate tags to the dorsal fin.

Summary

VHF radio and satellite-linked telemetry have greatly enhanced our understanding of biological processes through unrestrained monitoring of individual animals (reviewed in Cooke *et al.* 2004). However, detrimental effects associated with tag attachment must be of foremost concern and every effort to minimize negative impacts on the tagged individual should be undertaken (reviewed in Wilson and McMahon 2006). Reviews of cetacean telemetry studies conducted through the late 20th century (*e.g.,* Scott *et al.* 1990, Read *et al.* 1997, Mate *et al.* 2007) have described a reduction in the size and cost of transmitters and an increase in the number of cetacean studies utilizing telemetry methods. The most recent generation of satellite-linked tags is now small enough to effectively attach a single-pin design, which minimizes the risk of injury to the tagged individual and offers a broader geographic range and improved transmission duration.

Acknowledgments

This material is based upon work supported by BP and NOAA. Tracking data collected from previous bottlenose dolphin capture-release, health assessments were conducted under National Marine Fisheries Service Scientific Research Permit Nos. 522-1569-01 and 522-1527-00 (St. Joseph Bay), and 932-1905/MA-009526 (Georgia and Barataria Bay); and IACUC permit numbers UNCW 2004-012 (St. Joseph Bay) and UNCW 2007-016 (Georgia). Protocols for health assessment and tagging in Barataria Bay were reviewed and approved by a NOAA Animal Use and Care Committee. Research in Barataria Bay was funded as part of the cooperative agreement between NOAA, other federal and state Trustees and BP. Partial funding for research in Barataria Bay came from the Office of Naval Research and in St. Joseph Bay from the Disney Wildlife Conservation Fund. We would like to thank the Louisiana Department of Wildlife and Fisheries for logistical support during the Barataria Bay health assessment and follow-up monitoring; all of the participants in the four NOAA health assessments used in these analyses; and Wildlife Computers for manufacturing the new single-pin satellite-linked tag design.

Disclaimer

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of BP and/or state or federal natural resource trustees.

This publication does not constitute an endorsement of any commercial product or intend to be an opinion beyond scientific or other results obtained by the National Oceanic and Atmospheric Administration (NOAA). No reference shall be made to NOAA, or this publication furnished by NOAA, to any advertising or sales promotion which would indicate or imply that NOAA recommends or endorses any proprietary product mentioned herein, or which has as its purpose an interest to cause the advertised product to be used or purchased because of this publication.

Literature Cited

Balmer, B. C., R. S. Wells, S. M. Nowacek, *et al*. 2008. Seasonal abundance and distribution patterns of common bottlenose dolphins (*Tursiops truncatus*) near St. Joseph Bay, Florida, USA. Journal of Cetacean Research and Management 10:157–167.

Balmer, B. C., L. H. Schwacke and R. S. Wells. 2010. Linking dive behavior to satellite-linked tag condition for a bottlenose dolphin (*Tursiops truncatus*) along Florida's northern Gulf of Mexico coast. Aquatic Mammals 36:1–8.

Balmer, B. C., R. S. Wells, L. H. Schwacke, *et al*. 2011*a*. Evaluation of a single-pin, satellite-linked transmitter deployed on bottlenose dolphins (*Tursiops truncatus*) along the coast of Georgia, U.S.A. Aquatic Mammals 37:187–192.

Balmer, B. C., L. H. Schwacke, R. S. Wells, *et al*. 2011*b*. Relationship between persistent organic pollutants (POPs) and ranging patterns in common bottlenose dolphins (*Tursiops truncatus*) from coastal Georgia, USA. Science of the Total Environment 409:2094–2101.

Balmer, B. C., L. H. Schwacke, R. S. Wells, *et al*. 2013. Comparison of abundance and habitat usage for common bottlenose dolphins between sites exposed to differential anthropogenic stressors within the estuaries of southern Georgia, U.S.A. Marine Mammal Science 29:E114–E135.

Balmer, B. C., R. S. Wells, L. H. Schwacke, *et al*. In press. Integrating multiple techniques to identify stock boundaries of common bottlenose dolphins (*Tursiops truncatus*). Aquatic Conservation: Marine and Freshwater Ecosystems doi: 10.1002/aqc.2357.

Barbieri, M. M., W. A. McLellan, R. S. Wells, J. E. Blum, S. Hofmann, J. Gannon and D. A. Pabst. 2010. Using infrared thermography to assess seasonal trends in dorsal fin surface temperatures of free-swimming bottlenose dolphins (*Tursiops truncatus*) in Sarasota Bay, FL, U.S.A. Marine Mammal Science 26:53–66.

Cooke, S. J., S. G. Hinch, M. Wikelski, R. D. Andrews, L. J. Kuchel, T. G. Wolcott and P. J. Butler. 2004. Biotelemetry: A mechanistic approach to ecology. Trends in Ecology and Evolution 19:334–343.

Corkeron, P., and A. R. Martin. 2004. Ranging and diving behaviour of two 'offshore' bottlenose dolphins, *Tursiops* sp., off eastern Australia. Journal of the Marine Biological Association of the United Kingdom 84:465–468.

Eckert, S. A., and B. S. Stewart. 2001. Telemetry and satellite tracking of whale sharks, *Rhincodon typus*, in the Sea of Cortez, Mexico, and the north Pacific Ocean. Environmental Biology of Fishes 60:299–308.

Evans, W. E. 1971. Orientation behavior of delphinids: Radio telemetric studies. Annals of the New York Academy of Sciences 188:142–160.

Fish, F. E., and J. Rohr. 1999. Review of dolphin hydrodynamics and swimming performance. Technical Report 1801, SPAWAR System Center, San Diego, CA. 187 pp.

Gaskin, D. E., G. J. D. Smith and A. P. Watson. 1975. Preliminary study of the movements of harbour porpoises *(Phocoena phocoena)* in the Bay of Fundy using radiotelemetry. Canadian Journal of Zoology 53:466–1471.

Hamilton, J. H., R. D. Dillaman, W. A. McLellan and D. A. Pabst. 2004. Structural fiber reinforcement of keel blubber in harbor porpoise *(Phocoena phocoena)*. Journal of Morphology 261:105–117.

Harper, C. J., W. A. McLellan, S. A. Rommel, D. M. Gay, R. M. Dillaman and D. A. Pabst. 2008. Morphology of the melon and its tendinous connections to the facial muscles in bottlenose dolphins (*Tursiops truncatus*). Journal of Morphology 269:820–839.

Irvine, A. B., and R. S. Wells. 1972. Results of attempts to tag Atlantic bottlenose dolphins *(Tursiops truncatus)*. Cetology 13:1–5.

Irvine, A. B., M. D. Scott, R. S. Wells and J. H. Kaufmann. 1981. Movements and activities of the Atlantic bottlenose dolphin, *Tursiops truncatus*, near Sarasota, Florida. Fishery Bulletin 79:671–688.

Irvine, A. B., R. S. Wells and M. D. Scott. 1982. An evaluation of techniques for tagging small odontocete cetaceans. Fishery Bulletin 80:135–143.

Klatsky, L. J., R. S. Wells and J. C. Sweeney. 2007. Offshore bottlenose dolphins *(Tursiops truncatus)*: Movement and dive behavior near the Bermuda Pedestal. Journal of Mammalogy 88:59–66.

Mate, B. R., K. A. Rossbach, S. L. Nieukirk, R. S. Wells, A. B. Irvine, M. D. Scott and A. J. Read. 1995. Satellite-monitored movements and dive behavior of a bottlenose dolphin (*Tursiops truncatus*) in Tampa Bay, Florida. Marine Mammal Science 11:452–463.

Mate, B. R., R. Mesecar and B. A. Lagerquist. 2007. The evolution of satellite-monitored radio tags for large whales: One laboratory's experience. Deep-Sea Research Part II 54:224–247.

Meagher, E. M., W. A. McLellan, A. J. Westgate, R. S. Wells, D. Frierson, Jr. and D. A. Pabst. 2002. The relationship between heat flow and vasculature in the dorsal fin of wild bottlenose dolphins *Tursiops truncatus*. Journal of Experimental Biology 205:3475–3486.

Meagher, E. M., W. A. McLellan, A. J. Westgate, R. S. Wells, J. E. Blum and D. A. Pabst. 2008. Seasonal patterns of heat loss in wild bottlenose dolphins (*Tursiops truncatus*). Journal of Comparative Physiology B 178:529–543.

Norris, K. S., and T. P. Dohl. 1980. The structure and function of cetacean schools. Pages 211–261 *in* L. M. Herman, ed. Cetacean behavior: Mechanisms and functions. Wiley Interscience, New York, NY.

ONR. 1992. Marine mammal tagging and tracking. Workshop sponsored by the Office of Naval Research, National Marine Fisheries Service, and American Institute of Biological Sciences, Warrenton, VA.

ONR. 2009. Cetacean tag design workshop. Workshop sponsored by the Office of Naval Research, Arlington, VA.

Owen, E. C. G. 2003. The reproductive and ecological functions of the pair-bond between allied, adult male bottlenose dolphins, *Tursiops truncatus*, in Sarasota Bay, Florida. Ph. D. dissertation, University of California Santa Cruz, Santa Cruz, CA. 326 pp.

Pabst, D. A., S. A. Rommel and W. A. McLellan. 1999. The functional morphology of marine mammals. Pages 15–72 *in* J. E. Reynolds and S. A. Rommel, eds. Biology of marine mammals. Smithsonian Institution Press, Washington, DC.

Read, A. J., and A. J. Westgate. 1997. Monitoring the movements of harbour porpoises (*Phocoena phocoena*) with satellite telemetry. Marine Biology 130:315–322.

Read, A. J., A. J. Westgate, K. W. Urian, R. S. Wells, B. M. Allen and W. J. Carr. 1996. Monitoring movements and health status of bottlenose dolphins in Beaufort, NC using radio telemetry. Final contract report to the National Marine Fisheries Service, Southeast Fisheries Science Center, Charleston, SC. Contract No. 40-GENF-500160. 37 pp.

Read, A. J., A. J. Westgate, R. S. Wells, D. M. Waples, B. M. Allen, M. D. Scott and A. A. Hohn. 1997. Testing attachment techniques for satellite transmitters on bottlenose dolphins near Sarasota, Florida. Contract Report to National Marine Fisheries Service, Southeast Fisheries Science Center, Beaufort Laboratory, Beaufort, NC 28516. Contract No. 40ETNF700036. 12 pp.

Scholander, P. F., and W. E. Schevill. 1955. Counter-current vascular heat exchange in the fins of whales. Journal of Applied Physiology 8:279–282.

Scott, M. D., and S. J. Chivers. 2009. Movements and diving behavior of pelagic spotted dolphins. Marine Mammal Science 25:137–160.

Scott, M. D., R. S. Wells, A. B. Irvine and B. R. Mate. 1990. Tagging and marking studies on small cetaceans. Pages 489–514 *in* J. S. Leatherwood and R. R. Reeves, eds. The bottlenose dolphin. Academic Press, San Diego, CA.

Scott, M. D., A. A. Hohn, A. J. Westgate, J. R. Nicolas, B. R. Whitaker and W. B. Campbell. 2001. A note on the release and tracking of a rehabilitated pygmy sperm whale (*Kogia breviceps*). Journal of Cetacean Research and Management 3:87–94.

Scott, M. D., A. J. Westgate, R. S. Wells, *et al*. 2005. Appendix 1. Pages 15–48 *in* R. S. Wells, ed. Report to the Marine Mammal Commission on the small cetacean electronic tag attachment workshop. Mote Marine Laboratory, Sarasota, FL.

SolidWorks, 2012. SolidWorks Flow Simulation Software Package Ver. 2012. Dassault Systèmes SolidWorks Corp., Concord, MA.

Wainwright, S. A., W. D. Biggs, J. D. Currey and J. M. Gosline. 1982. Mechanical design in organisms. Princeton University Press, Princeton, NJ.

Waples, D. M. 1995. Activity budgets of free-ranging bottlenose dolphins (*Tursiops truncatus*) in Sarasota Bay. M.S. thesis, University of California Santa Cruz, Santa Cruz, CA. 61 pp.

Weber, P. W., L. E. Howle, M. M. Murray and F. E. Fish. 2011. Computational evaluation of the performance of lifting surfaces with leading edge tubercles. Journal of Aircraft 48:591–600.

Wells, R. S. 2005. Report to the Marine Mammal Commission on the Small Cetacean Electronic Tag Attachment Workshop, June 11–12, 2003, Sarasota, Florida. Purchase Order No. T03326587. 73 pp.

Wells, R. S. 2009. Identification methods. Pages 593–599 *in* W. F. Perrin, B. Würsig and J. G. M. Thewissen, eds. Encyclopedia of marine mammals. Second edition, Elsevier, Inc., San Diego, CA.

Wells, R. S., K. Bassos-Hull and K. S. Norris. 1998. Experimental return to the wild of two bottlenose dolphins. Marine Mammal Science 14:51–71.

Wells, R. S., H. L. Rhinehart, P. Cunningham, J. Whaley, M. Baran, C. Koberna and D. P. Costa. 1999. Long distance offshore movements of bottlenose dolphins. Marine Mammal Science 15:1098–1114.

Wells, R. S., H. L. Rhinehart, L. J. Hansen, *et al*. 2004. Bottlenose dolphins as marine ecosystem sentinels: Developing a health monitoring system. EcoHealth 1:246–254.

Wells, R. S., G. A. Early, J. G. Gannon, R. G. Lingenfelser and P. Sweeney. 2008. Tagging and tracking of rough-toothed dolphins (*Steno bredanensis*) from the March 2005 mass stranding in the Florida Keys. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SEFSC-574. 44 pp.

Wells, R. S., C. A. Manire, L. Byrd, D. R. Smith, J. G. Gannon, D. Fauquier and K. D. Mullin. 2009. Movements and dive patterns of a rehabilitated Risso's dolphin, *Grampus griseus*, in the Gulf of Mexico and Atlantic Ocean. Marine Mammal Science 25:420–429.

Wells, R. S., D. A. Fauquier, F. M. D. Gulland, F. I. Townsend and R. DiGiovanni, Jr. In press. Evaluating postintervention survival of free-ranging odontocete cetaceans. Marine Mammal Science doi: 10.1111/mms.12007.

Westgate, A. J., and A. J. Read. 1998. Applications of new technology to the conservation of porpoises. Marine Technology Society Journal 31:70–81.

Westgate, A. J., A. J. Read, T. M. Cox, T. D. Schofield, B. R. Whitaker and K. E. Anderson. 1999. Monitoring a rehabilitated harbor porpoise using satellite telemetry. Marine Mammal Science 14:599–604.

Westgate, A. J., W. A. McLellan, R. S. Wells, M. D. Scott, E. M. Meagher and A. A. Pabst. 2007. A new device to remotely measure heat flux and skin temperature from free-swimming dolphins. Journal of Experimental Marine Biology and Ecology 346:45–59.

Wilson, R. P., and C. R. McMahon. 2006. Measuring devices on wild animals: What constitutes acceptable practice? Frontiers in Ecology and the Environment 4:147–154.

Winn, J. B., B. Woodward, M. Moore and M. Peterson. 2008. Modeling whale entanglement injuries: An experimental study of tissue compliance, line tension, and drawlength. Marine Mammal Science 24:326–340.

Received: 1 April 2013
Accepted: 2 August 2013