Developing robust large whale satellite tags through follow-up studies

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ABSTRACT

The use of satellite tags has yielded important information to better understand cetacean ecology and to improve cetacean conservation. However, tag deployment duration has been highly variable and typically shorter than their battery life on most large whale species. Between 2011 and 2018, 80 consolidated satellite tags were deployed in North Atlantic humpback whales (*Megaptera novaeangliae*) in the Gulf of Maine (GoM) to study whale movements, to assess tag impacts, and to understand causes of tag rejection and tag failure. The strong site fidelity of individual whales to the GoM, long feeding ground residency, and high observer effort allowed repeated sightings of animals instrumented with satellite tags. In early deployments multiple structural deficiencies were documented on the tags, revealing the need to improve the mechanical design and manufacturing of the instruments. These tag deficiencies not only resulted in short tag transmission durations, but also in negative health impacts on individual animals. Incremental modifications to the mechanical design and the manufacturing processes to resolve the observed deficiencies included: (1) changes in the anchor tip, retention devices, and anchor articulation, (2) the removal of the interface between the transmitter housing and the anchor and (3) the redesign of the posterior end of the tag. More robust instruments were produced by welding deficient tag parts or by using 3-dimension (3-D) metal printing processes to manufacture integrated instruments. Deployments of redesigned satellite tags resulted in 65–85% significantly longer average transmission durations when compared to earlier designs that showed structural deficiencies. This study highlights the importance of developing satellite tagging technology in association with follow-up monitoring of tagged individuals and provides new tag designs that are structurally more robust and less impactful for use with large cetaceans.

KEYWORDS: HUMPBACK WHALE; TECHNOLOGY DEVELOPMENT; SATELLITE TAGGING; TELEMETRY

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INTRODUCTION

Investigating the complex spatial ecology of wide-ranging marine predators is difficult, yet a comprehensive understanding of movement dynamics and habitat use patterns is required to describe their role in the ecosystem and to evaluate their vulnerability to anthropogenic threats (Block *et al*., 2011; McGowan *et al*., 2017). Satellite telemetry has greatly improved knowledge of the seasonal distribution and migratory cycle of several cetacean populations (Zerbini *et al*., 2006; 2011; Citta *et al*., 2012; Double *et al*., 2014; Hauser *et al*., 2014; Andrews-Goff *et al*., 2018; Hucke-Gaete *et al*., 2018; Modest *et al*., 2021; Bedrinaña-Romano *et al*., 2022), especially in regions that are remote or otherwise inaccessible to researchers (Zerbini *et al*., 2006; Heide-Jørgensen *et al*., 2012). Satellite tracking has revealed the existence of previously unknown habitats (e.g., Mate *et al*., 1997; 2015; Garrigue *et al*., 2015), and has provided unprecedented insights into cetacean habitat use (Zerbini *et al*., 2015; Lagerquist *et al*., 2019; Derville *et al*., 2020), diving behaviour (Schorr *et al*., 2014; Barlow *et al*., 2020; Rone *et al*., 2022), predation and foraging (e.g., Pitman *et al*., 2015; Weinstein & Friedlaender, 2017; Kettemer *et al*., 2023; Palacios *et al*., 2022), physiological adaptations (Pitman *et al*., 2020) and navigation (Horton *et al*., 2011; 2017).

Telemetry is also an important research tool to obtain key information for conservation and management, including evaluating the vulnerability of cetaceans and their habitats to anthropogenic threats. Examples include assessing population structure (e.g., Baumgartner & Mate, 2005; Heide-Jørgensen *et al*., 2006; Wade *et al*., 2006; Prieto *et al*., 2014; Ramp *et al*., 2024), developing dynamic management tools to predict whale occurrence (Hazen *et al*., 2017), proposing and evaluating the adequacy of critical habitats (e.g., Zerbini *et al*., 2015; Panigada *et al*., 2017), biologically important areas (Hamilton *et al*., 2021; Kratofil *et al*., 2023; Calambokidis *et al.,* 2024) and marine protected areas (de Castro *et al*., 2014; Zhang *et al*., 2024). Satellite tracking has also been used to assess the overlap of cetacean habitat with human activities (e.g., Guzman *et al.*, 2013; Citta *et al*., 2014; Irvine *et al.,* 2014; Rosenbaum *et al*., 2014; Weinstein *et al*., 2017; Johnson *et al*., 2022) and to generate data over long timeframes and large spatial scales to understand how shifts in habitat use occur in response to climate change (Hauser *et al*., 2017; Bedriñana-Romano *et al*., 2022; Horton *et al*., 2020; Citta *et al*., 2023).

Almost all satellite tags for large whales are invasive (i.e., disruptive to the integrity of the skin) to some extent, with most involving some degree of sub-dermal penetration. In recent years, tracking whales for longer periods of time (several weeks to several months) has been better achieved with the use of instruments that are nearly or fully embedded in the body of a whale (Mate *et al*., 2007; Andrews *et al*., 2019). These tag designs have recently been referred to as 'consolidated' or Type C tags (Andrews *et al*., 2019; IWC, 2020), but 'implantable', 'transdermal,' and 'deep implant' tags are terms also used in the literature by regulatory agencies and tag manufacturers. Consolidated tags have been widely used in large whale tracking studies for decades (see various examples in Johnson *et al*., 2022) and are typically designed to anchor beneath the blubber-muscle interface (i.e., the fascia) but with the antenna and other componentry still protruding from the whale. However, for the most part, transmission duration has been lower than the expected battery life, and the reasons for premature cessation of transmission reception remain poorly understood. Further, penetration through the blubber and fascia has raised concerns about the possible adverse effects of invasive instruments on the health of individual whales (Weller, 2008; ONR, 2009; Moore *et al*., 2013; IWC, 2020).

In 2011, a study to deploy satellite tags and conduct follow-up monitoring on well-studied North Atlantic humpback whale (*Megaptera novaeangliae*) individuals in the Gulf of Maine (GoM, northeast coast of the USA) was initiated to assess performance of consolidated tags and any potential effects they may have on whales while evaluating habitat use. Specifically, the primary goals of this research were to (1) evaluate tag deployment and tag design and how they relate to tag functional life, (2) characterise the range of demographic, physical and physiological effects of tagging, (3) evaluate behavioural responses to tagging, and (4) obtain data on movements and habitat use of GoM humpback whales. In this paper, we present an assessment of tag designs used throughout the study period, shortcomings related to early satellite tags, measures adopted to develop more robust instruments, and an assessment of tag functional life after these measures were implemented. Evaluations of physical/physiological, behavioural and demographic effects of consolidated tags on humpback whales in the GoM are presented, respectively, in Gulland *et al.* (2024) and Robbins *et al.* (in prep, a and b).

MATERIALS & METHODS

Humpback whales in the Gulf of Maine

The experimental design of this study required regular resightings of tagged individuals to document satellite tags and the tag site over periods of time ranging from several months to years. Humpback whales in the GoM are ideal for this type of study for several reasons. Humpback whales can be individually identified using natural marks including the shape and colouration pattern of the ventral surface of their flukes and dorsal fin (Katona & Whitehead, 1981). Humpback whales in the GoM have been the subject of photo-identification studies for over 40 years and the life history of many individuals is well documented in the Gulf of Maine Humpback Whale Catalog (Center for Coastal Studies, Provincetown, MA, USA). These whales occur in predictable habitats during their feeding season (March–December) and there are dedicated feeding ground-wide photo-identification efforts that provide the opportunity for multiple resightings of known individuals within and between seasons (Robbins, 2007). Finally, a relatively large whale watching industry operates in the GoM[11], with on-board naturalists who collect and contribute photos and sighting data to the Gulf of Maine Humpback Whale Catalog.

Consolidated tag design

Consolidated tags are designed to nearly fully penetrate the skin of the target animal, leaving just a small portion of the posterior end of the tag protruding from the whale's body. They embed in the blubber and anchor at or below the relatively stiff connective tissue located between the blubber and the muscle (also known as the fascia). The mechanical design of these tags typically comprises two main parts: (1) the anchoring system (or anchor) which often contains a sharp tip to facilitate the tag penetration and retention elements to hold the tag in the surrounding tissue, and (2) the electronics housing (where the transmitter, batteries and other electronic components are installed) (Fig. 1A). The anchoring systems are cylindrical in shape and vary from 20 to 190 mm in length and from 8 to 24 mm in diameter. A sharp, needle-like tip or a multi-bladed, flat, conical or triangular-shaped tip is attached to the anterior end of a shaft, and one or more rows of retention wires, flaps, barbs or petals are attached to the anchor shaft (e.g., Heide-Jørgensen *et al*., 2003; 2006; Zerbini *et al*., 2006; Mate *et al*., 2007; Gales *et al*., 2009). These retention elements are passively or actively deployed upon tag penetration. They vary in shape, texture and degree of sharpness. Anchoring systems have evolved over the years and various designs have been used by different research groups (ONR, 2009). Some illustrative examples can be found in Mate *et al*. (2007, Fig. 2) and Hauser *et al*. (2010, Fig. 1). The electronics package is typically housed in a cylindrical tube (hereafter referred to as the transmitter housing), with dimensions ranging from 100 to 230 mm and 19 to 24 mm in diameter. In some cases, retention elements like the ones described above for anchoring systems can also be installed on the transmitter housing. An antenna, a conductivity sensor (or saltwater switch) and, in some cases, other sensors are present at the posterior (outer) end of the tag, external to the tag housing (Fig. 1A). The transmitter housing is mounted on (screwed into) the anchor via a 10 to 20 mm pin welded to the base of the housing until both tag parts are flush against each other. This interface has been needed to accommodate the use of different anchor designs by different research groups. The overall length of these tags can reach up to 300 mm. Both the transmitter housing, the anchor and the retention elements are made of surgical-quality stainless steel.

The initial tag design used in this study (in 2011) is illustrated in Fig. 1A. A unique feature of this tag's anchor was the presence of a single articulation point, with the anchor made of two parts (Fig. 1A and 2B). The anterior (80 mm) section of the anchor disarticulated from the posterior section after deployment and a 40 × 2 mm multi-braided stainless-steel wire rope maintained the coupling between the two anchor parts (Fig 1A, Fig. 2B, 2D). The articulation was designed for two purposes: (1) it was expected to provide a more stable attachment because vibration from the supracutaneous part of the transmitter would be reduced at the anchoring point if the transmitter were decoupled from the anchor, and (2) it could compensate, at least partially, for shearing forces acting at the muscle-blubber interface (Moore *et al*., 2013; Moore & Zerbini, 2017). After deployment, the two sections were intended to pull away from each other and separate by as much as 5 mm, allowing the proximal and distal ends of the tag to move in different directions, thereby potentially allowing the anchor to

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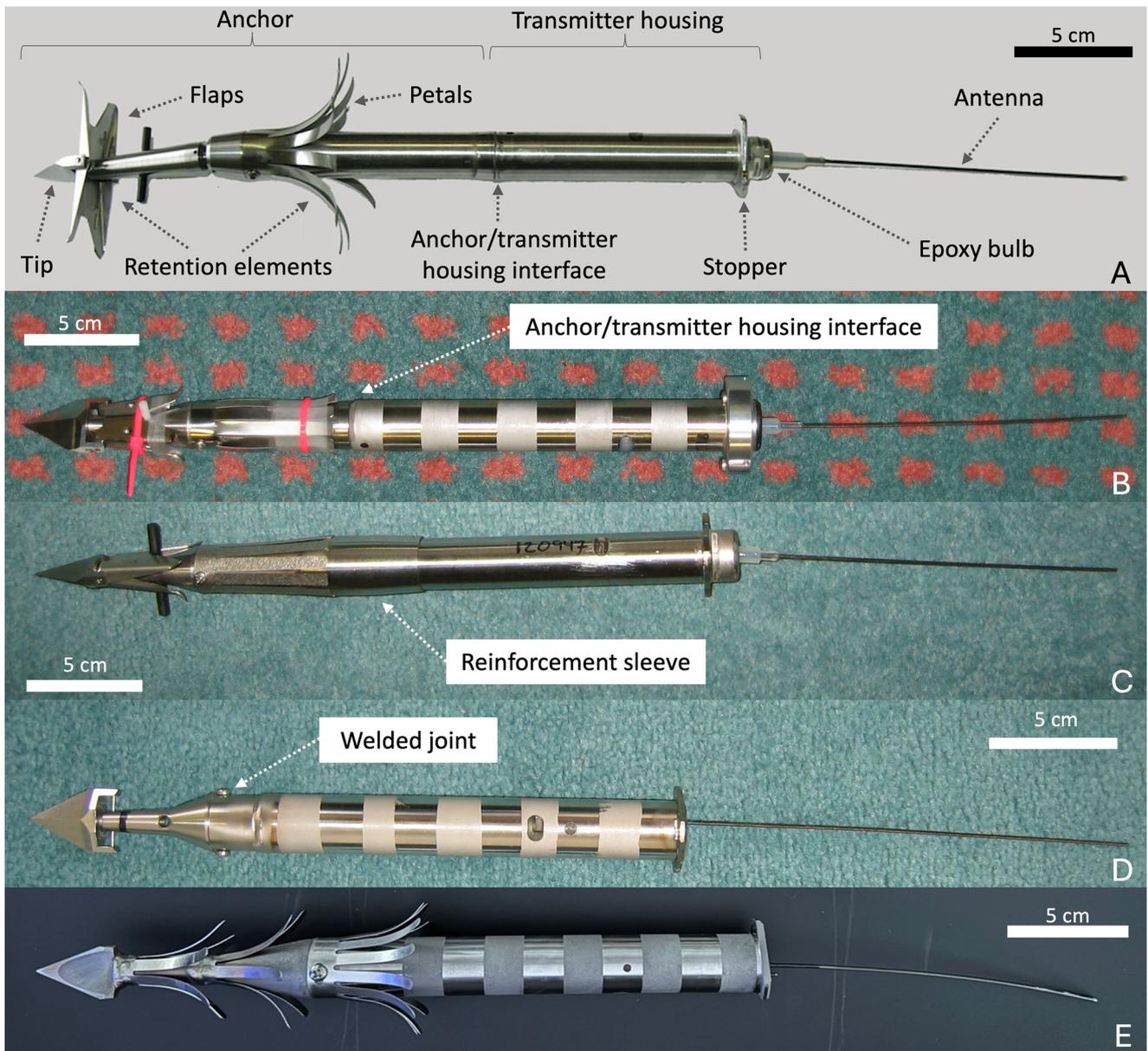[11] *https://wwhandbook.iwc.int/en/case-studies/united-states-of-america-gulf-of-maine*

Figure 1: Consolidated satellite tag designs deployed in Gulf of Maine humpback whales between 2011 and 2018. A: Articulated tag; B: Interfaced tag; C: Reinforced tag; D: SPOT-303 (Welded); E: SPOT-372 (Welded and DMLS). Note that retention elements are shown in deployed position in A and E, flush against the body of the tag in pre-deployment position in B and C, and are not shown in D to facilitate visualisation of the welded joint.

compensate for shearing (Gales *et al.*, 2009). The anchor design included a triangular-shaped tip, a set of actively deployed 'flaps' and a set of retention petals (Table 1 and Fig. 1A). The electronics package consisted of a Wildlife Computers SPOT transmitter (Mold AM-S193), 172 mm in length and 22 mm in diameter (Supplementary Material 1). An epoxy 'bulb' (epoxy that encapsulates the electronics) projected 15.8 mm from the posterior end of the stainless-steel housing. The wet-dry sensor (or saltwater switch) was implemented as a ring around the bulb and the Argos antenna projected 165 mm from the center of the bulb (Fig. 1A). A triangle-shaped stop plate (37 mm in its maximum width) was welded at the edge of the tag housing (Fig. 1A). The stopper serves as an attachment point for the carrier required for deployment of tag using pneumatic tag delivery systems (e.g., the Air Rocket Transmitting System [ARTS], Heide-Jørgensen *et al*., 2001) and to prevent the inward migration of the tag into the body of the whale after deployment (Gales *et al.*, 2009). The transmitter housing was mounted in the anchor via a 10 mm M6 size threaded pin (Fig. 3A), which screwed into an opening in the center of the anchor shaft (Fig. 3C). Metal glue was applied to the thread and to the metal surface of both sides of the interface between
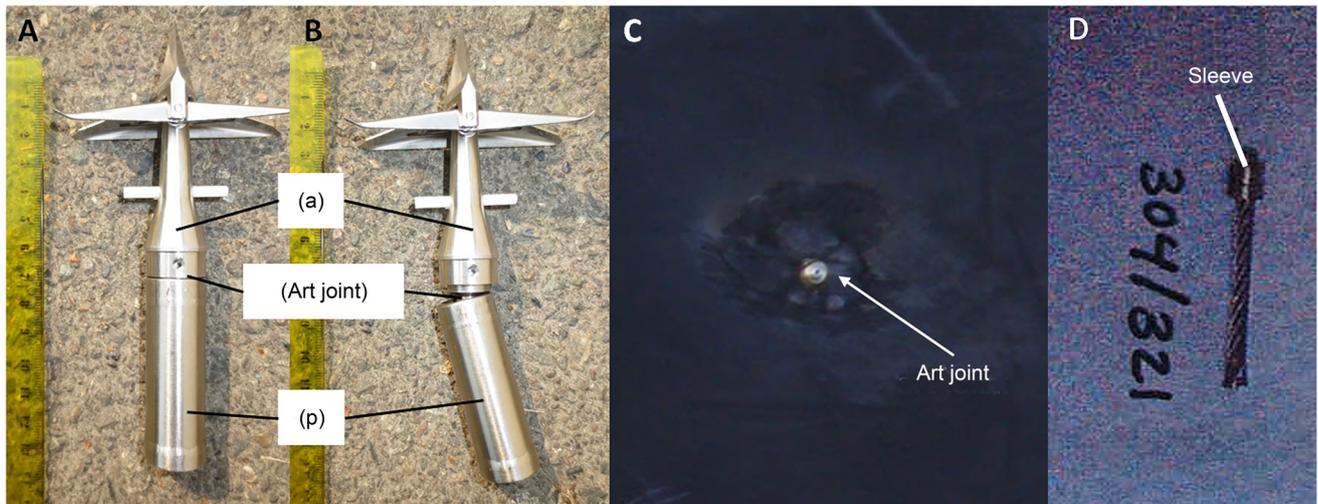
Figure 2: Example of an articulated anchor design. The retention plates are in the deployed position and the retention petals are removed to expose the articulation. A: anterior (a) and posterior (p) anchor sections coupled at the articulation joint (art joint) for deployment; B: anchor sections decoupled showing anchor flexing at the articulation (art joint); C: anterior section of the anchor attached to a whale after the transmitter and posterior section were shed; the articulation joint (art joint) is exposed; D: braided cable and stop sleeve.

Table 1

Description of satellite tag designs deployed in Gulf of Maine humpback whales between 2011 and 2018 (see Figure 1 for illustrations and text for details).

Tag design	Tag category	Anchor design	Anchor/transmitter interface	Number deployed	Deployment year
Articulated (Fig. 1A)	Non-integrated	Multifaceted (4 faces) triangular-shaped tip 29 mm long and 25 mm across the base with two cutting edges. Retention elements included a spring-loaded set of actively deployed retention 'flaps' 26 mm wide, 40 mm long and a set of 12 passively deployed retention 'petals' 50 mm in length, 5.8 mm in width and 0.26 mm in thickness. An anchor articulation 80 mm from the tip was present in this design.	10 mm threaded pin used to attach the transmitter to the anchor.	19	2011
Interfaced (Fig. 1B)	Non-integrated	Same as the Articulated tag without the articulation.	10 mm threaded pin used to attach the transmitter to the anchor.	16	2012
Reinforced (Fig. 1C)	Integrated	Same as the Articulated tag without the articulation	10 mm threaded pin used to attach the transmitter to the anchor and a stainless-steel reinforced sleeve welded to the distal end of the anchor to protect the interface.	3	2013
SPOT-303 (Fig. 1D)	Integrated	Same as the Articulated tag without the articulation.	Transmitter welded to the anchoring system.	12	2013, 2015
SPOT-372 (Fig. 1E)	Integrated	Three-bladed pyramidal shaped tip. Three sets of retention petals. One set with six petals at the base of the tip, a second set with six petals located 33 mm posterior to the first set and a third set with 12 petals at the base of the transmitter housing. Petal dimensions are 38 mm long and 4.5 mm wide. First set of petals is 0.5 mm thick; the second and third sets are 0.38 mm thick.	Two versions were produced: • Welded version: transmitter welded to the anchoring system • DMLS version: entire tag manufactured as single piece using a DMLS (3-D printing) process.	15 (Welded), 15 (DMLS)	2015 (Welded), 2018 (DMLS)

the anchor and the housing to minimise chances that the transmitter housing would unscrew from the anchor after deployment.

Rings were etched on the body of the transmitter housing to evaluate the outward migration rate of the tag as animals were resighted over time. In 2011, the rings were limited to the upper 35 mm of the posterior
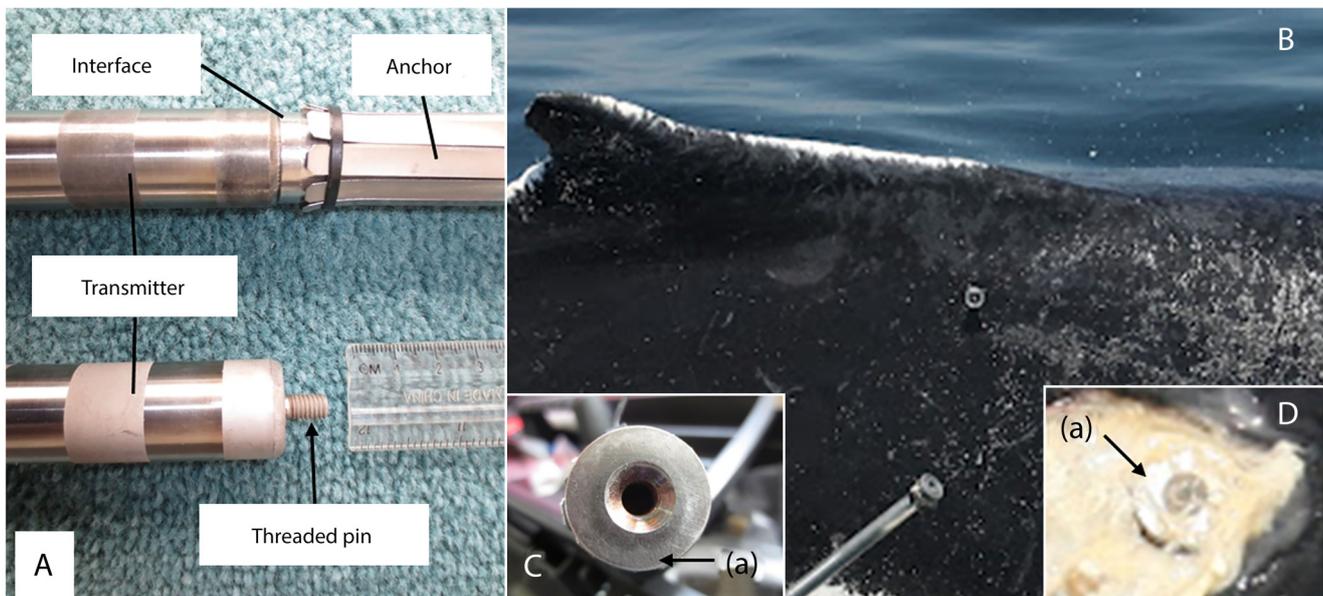
Figure 3: Anchor/transmitter interface breakage observed with Gulf of Maine humpback whales. A: transmitter with the anchor attached (top) showing the location of the interface and (bottom) without the anchor showing the threaded pin that connects the tag sections; B: tag on a humpback whale; C: posterior end of the anchor (a) showing the aperture where the transmitter threaded pin screws in; D: posterior end of the anchor (a) coming out of the body of the individual shown in B. Note the clear indication of failure at the interface between anchor and transmitter.

end of the tag, but in all subsequent years they were etched 16 mm apart along the entire housing (Fig. 1B, D and E; see also Kennedy *et al.*, 2024) and could be reliably viewed across a wide range of angles and photo-quality.

Selection of individuals for tagging

In this study, individuals with the following characteristics were selected for tagging by a population expert (JR) based on their life history and demographic traits: (1) regular annual return to the primary study area, (2) frequent within-season re-sighting rates, (3) known sex and age class as well as detailed calving history (for females), (4) apparent good body condition at the time of tagging, and (5) no recent history of poor health (defined as pale skin, significant cyamid coverage, unhealed injuries and/or lower than average apparent body condition). Candidates were also selected to obtain a balanced sample of males and females. The sex of tagged individuals had been determined from prior genetic analysis (Bérubé & Palsbøll, 1996) and was often further supported by prior observation of the genital slit (Glockner, 1983) and/or, in the case of females, calving history. Satellite tags were deployed only on adults without a dependent calf in the year of tagging to minimise potential survival effects considering that juveniles and lactating females are known to have lower annual survival probabilities (Robbins, 2007). Age class was assigned based on the number of elapsed years since the first sighting, which was based either on the year of birth (exact age) or a subsequent sighting after independence (minimum age). Individuals younger than the earliest known age at parturition in this population (five years; Clapham, 1992) were considered 'juveniles' and were not tagged.

Deployment of consolidated satellite tags

In 2011, 2012, 2013, 2015 and 2018, a total of 80 consolidated Argos satellite tags were deployed on 79 humpback whales in the GoM. For one individual, the tag did not penetrate upon deployment and fell off immediately. This whale was tagged again four days after the first attempt. Five different tag designs were used throughout this study (Fig. 1). These are referred to as 'articulated,' 'interfaced,' 'reinforced,' 'SPOT-303' and 'SPOT-372' tags. The anchor design, configuration of the anchor/transmitter interface, sample size and deployment years are summarised in Table 1. These designs reflect incremental modifications required to improve

the structural integrity of the tags following deficiencies identified both in the field and through systematic laboratory experiments as described below.

Upon receiving from the manufacturer, tags were cleaned with acetone and detergent soap to remove metal and oil residuals, then rinsed in water and air dried. They were then placed in a sterilisation sleeve and sterilised with ethylene oxide gas for 24 hours. Tags were only removed from the sterilisation packaging immediately prior to deployment. Handling of the tag after removal from the sterilisation sleeves was done with sterilised surgical gloves. Pre-deployment preparation and sterilisation of satellite tags were consistent with best practices for cetacean tagging (Andrews *et al.*, 2019).

Tag deployments were performed from the bow or the bow sprit of the R/V Shearwater (a 12.1 m twin-screw Jarvis Newman motor vessel) or the R/V Ibis (a 10.7 m, dual outboard, rigid-hulled boat). Whales were approached by an experienced captain (DKM) at distances ranging from 3–10 m and tags were deployed by experienced personnel (ANZ, ASK) with a modified version of the ARTS (Heide-Jørgensen *et al.*, 2001), and compressed air pressures ranging from 9 to 11 bars. The tags were connected to a tag carrier (Fig. 4A) using a metal 'ring' attached to the stopper (Fig. 4B, 4C). The carrier separated from the ring on impact (Fig. 4C) and was collected from the water after deployment (Gales *et al.*, 2009; Andrews-Goff *et al.*, 2018). The tagger attempted to deploy the tags in a position on the whale that was relatively high on the body, either slightly cranial (within 3–4 feet), or immediately ventral to the dorsal fin.

Photographic and video documentation, deployment characteristics and estimation of tag egress

Deployments were documented using regular and slow-motion video cameras to evaluate the characteristics of tag deployment, including the trajectory of the tag and the tag carrier, and tag penetration upon contact with the whale skin. The tag site was also photographed prior to, and during a one-hour focal follow after tag deployment (Gulland *et al.*, 2024; Robbins *et al.*, in prep, b). After the deployment day, whales were relocated on a weekly or bi-weekly basis in the tagging year based on telemetry data. Later, they were found opportunistically by targeting historical site preferences and aggregation sites. Follow-up monitoring was also facilitated by collaborating observers and commercial whale watching vessels, who obtained and shared photographs of the tagged whale on an opportunistic basis. In this study, photographs were used to assess the apparent condition of the tag, rate of tag outmigration, presence of biofouling, potential damage to the tag body or other tag elements.

For tags deployed between 2011 and 2015, the length of exposed tag was measured from photographs on the day of deployment through the follow-up period while the tags were still attached. These measurements were intended to estimate tag egress using the etched rings (Fig. 1B, D and E) of the tags for scale. Because most
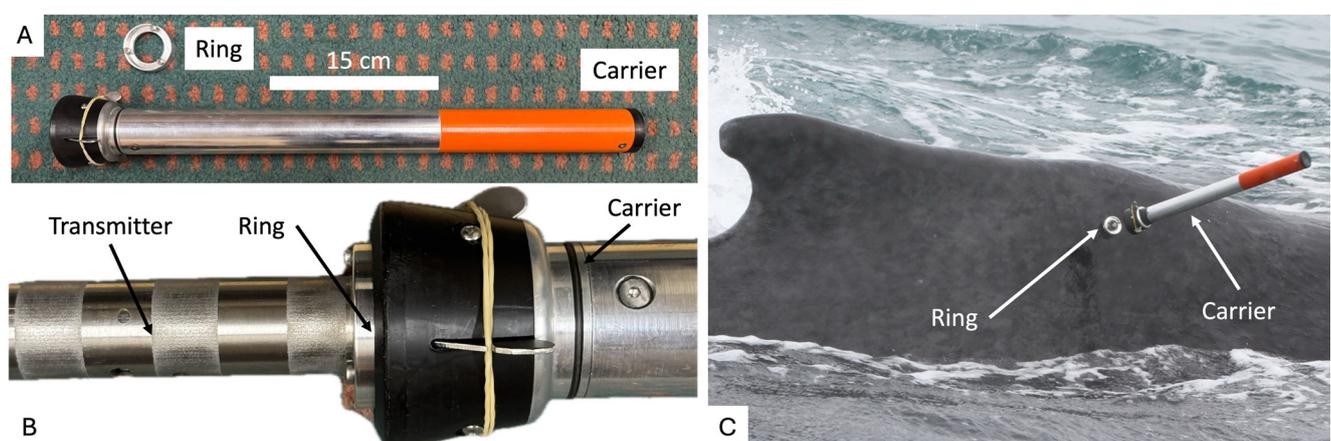

Figure 4: The carrier and deployment ring used for deployment of consolidated satellite tags (A) on humpback whales in the Gulf of Maine, a magnified view of the connection of the tag and the carrier via a metal ring (B) and a field photograph showing the carrier separating from the tag and the metal ring upon deployment (C).

tags were not inserted perpendicular to the skin surface, two measurements were made for each relevant photo, one along each edge of the tag to the skin. If the skin surface could not be determined at the tag (due to extruded tissue, see examples in Gulland *et al.*, 2024), then the skin level was assessed from nearby, undisturbed skin. Images selected for measurement were for those in which the skin surface at the tag insertion was approximately perpendicular to the camera. This angle allowed the best opportunity to measure the full length of the exposed tag.

Tag functional life and statistical analysis

Transmission duration was used as a measure of the functional life of the tag and evaluated in relation to variables (covariates) hypothesised to influence tag retention. These variables included tag type, tag placement on the body, initial depth of penetration, the tagged animal's age and sex and the side of the whale's body (left or right) where the tag was deployed. Tag placement was evaluated from a circumferential (vertical plane) and cranio-caudal (horizontal plane) position as described in Gulland *et al.* (2024). Circumferential placement included deployments in the 'upper' (dorsal) flank or in the 'lower' (lateral) flank. Cranio-caudal placement was characterised as 'cranial' (cranial of the dorsal fin and the dorsal hump), 'central' (near the dorsal fin and hump), or 'caudal' (caudal to the dorsal fin). Depth of tag penetration upon deployment was estimated using a photogrammetric method based on the known dimensions of the tag, the length of tag exposed and the angle of the tag relative to the plane of the body as described in Gulland *et al.* (2024, Supplementary Material S1).

Statistical analyses were conducted using Generalised Linear Models (GLMs) in package MASS 7.3.60.0.1 (Venables and Ripley, 2002) of the open-source software R (version 4.3.3, R Core Development Team 2024). The response variable, tag duration, was log-transformed to reduce skewness and a saturated model was specified treating tag category, tag placement, and sex as factor covariates and age at tagging and tag penetration depth as numerical variables. The most parsimonious model was selected based on the lowest Akaike Information Criterion (AIC) using a stepwise process with function step in package stats (version 4.3.3, R Core Development team, 2024). Seven individuals were not included in the statistical analysis because tags were accidentally deployed on the dorsal fin (n = 4), were too low on the body for transmissions to be reliably received or for consistent photographic documentation of the tag site during follow-up (n = 1), or did not properly attach and fell off immediately after deployment (n = 1). A seventh tag that was prematurely removed during an entanglement event (Gulland et al., 2024) was also not included.

Development of new satellite tag designs

The articulated tag design shown in Fig. 1A served as the basis for the improvements developed during this study. These improvements were made in two phases, and a tag design was produced at the end of each phase. Design changes in Phase 1 were carried out to address the structural deficiencies immediately after they were documented during follow-up of tagged whales. These changes were needed on an urgent basis to reduce the risks of health effects from tagging for any further tag deployments (see Gulland *et al.*, 2024 for details on tag effects to individual whales). In Phase 2, an improved satellite tag was designed based on findings from field deployments and from laboratory experiments planned to assess the structural robustness of the housing and other tag elements. These experiments included a suite of impact tests, and insertion and removal of miniature and life-size tags into hard durometer rubber and into cetacean tissue. Laboratory experiments are described in detail in Moore & Zerbini (2017) and in Supplementary Material 2.

RESULTS

Detailed follow-up of tagged humpback whales and subsequent laboratory experiments revealed important design deficiencies in the consolidated tags deployed on humpback whales in the GoM in 2011, 2012 and 2015. These are summarised in Table 2 and described in more detail below, along with remediation measures taken to strengthen the tags and an evaluation on how these measures improved transmission reception duration.

Table 2

Summary of structural issues and subsequent design improvements made to the consolidated satellite transmitters deployed in Gulf of Maine humpback whales

Tag element	Documented fault	Documentation method	Required change	Year change was first implemented
Anchor articulation	Breakage of the anchor articulation left anterior portion of the anchoring system caused premature detachment of the transmitter and left the anchor tip and retention elements embedded in the body of tagged animals after tag loss.	Visual and photographic documentation of the whale and the tag site over multiple encounters.	Removal of the articulation.	2012
Anchor/ transmitter interface	Breakage of the anchor/transmitter interface caused premature detachment of the transmitter, and the anchor embedded in the body after tag loss.	Visual and photographic documentation of the whale and the tag site over multiple encounters.	Removal and redesign of the anchor/transmitter interface.	2013
Posterior end of the tag (epoxy bulb)	Cracking or breakage of the epoxy resulted in tag failure and loss of transmissions.	Visual and photographic documentation of the whale and tag site.	Redesign of the posterior end of the transmitter.	2013
Tag housing (welding joint)	Removal of the anchor/transmitter interface was originally performed by replacing that interface by a welding joint. Resightings of an animal instrumented with tags in which the anchor was welded to the transmitter revealed breakage of the joint, suggesting the need to improve robustness of the satellite tag.	Visual and photographic documentation of the tag site and impact tests to assess tag robustness.	Ensure welding is properly conducted or production of tags as single pieces using 3-D printing techniques (DMLS).	2018 (DMLS)
Retention elements	Possible breakage of retention flaps would reduce attachment duration and could leave parts of the tag embedded in the body after tag loss.	Impact tests to assess robustness.	Redesign of retention elements.	2015
Tag tip	Blade configuration of the tip resulted in changes in tag trajectory upon implantation, resulting in sub-optimal attachment of the tag.	Impact tests to assess robustness.	Redesign of the anchor tip.	2015

Structural tag design faults documented in the field

The anchor articulation

Follow-up monitoring revealed that, for many deployments, the joints within the anchor articulation failed and the posterior portion of the anchor and the transmitter detached prematurely, resulting in shorter than expected durations (Fig. 2). Photographic evidence indicates that breakage occurred at the braided cable or at the stop sleeves (Fig. 2D) crimped to each end of the cable and used to lock the cable into the two anchor sections. It was hypothesised that breakage of the cable system occurred either upon deployment or post-deployment because the system could not withstand stress on the stop sleeves caused by impact forces, by material fatigue and/or by pulling forces, possibly including shearing. Breakage of the anchor articulation was confirmed in 26.3% (n = 5) of the 19 tags deployed in 2011, the only year that the articulated tag design was used. In addition, failure of the articulation was suspected in 42.1% (n = 8) of these tags given that follow-up photographs suggested the transmitters had separated from the anchor (e.g., the transmitter appeared loose, moving in and out of the tag wound between re-sights) and the appearance of the tag wound was consistent with those in which breakage was confirmed. The actual breakage proportion is unknown, but it was likely higher because failure of the articulation may not have always been visible despite the regular whale resighting effort.

The anchor-transmitter interface

Another structural deficiency was found at the interface between the anchoring system and the transmitter housing (Fig. 3A). Breakage and/or bending of the tag at the anchor-transmitter housing interface was documented for 25% (n = 4) of the 16 deployments in 2012 (Fig. 3). Bending started as early as the day after

deployment in one poorly penetrating attachment to the dorsal fin and the transmitter reception ceased nine days later in that case (Supplementary Material 3). Close examination of photographs suggested the breakage of the anchor-transmitter housing occurred at the welding of the threaded pin at the base of the housing (Fig. 3D). Bending/breakage was potentially caused by impact upon deployment, or forces on the tag after deployment (e.g., contact with objects in the environment, the sea floor or other whales).

Possible damage to the epoxy bulb

Transmissions were received for three days from one tag attached to a whale in 2012, but reception stopped when the conductivity switch was covered by tissue and was no longer able to detect tag exposure to the air. Transmissions resumed 15 days after deployment and the tag worked for another 31 days (Fig. 5A) when the transmissions ceased. This individual was re-sighted multiple times with the non-transmitting tag from 57 to 79 days after tag deployment (Fig. 5B), a period during which photographs of the tag and the tag site indicated no apparent external damage to the tag. The lack of transmissions over this period was interpreted as likely due to damage to the epoxy bulb. This portion of the epoxy-encapsulated electronics was relatively exposed and, therefore, vulnerable. Damage could occur at deployment through the formation of fissures (e.g., by contact with the tag carrier) and, over time, these fissures could develop further and eventually allow for water intrusion and permanent failure of the electronics. Damage could also occur due to the tag's potential contact with objects in the environment, the sea floor or with other whales after deployment. This external cause was also hypothesised based on observations of tags deployed in other regions (Supplementary Material 4), but it is not possible to rule out that other causes (e.g., electronic failure) were responsible for the premature cessation of tag transmission.

The anchor-transmitter welding joint

Breakage of the welding joint between the anchor and the transmitter was documented in one integrated tag deployed in 2015 (Fig. 6A, Supplementary Material 2, Fig. S13) and remained active for 112 days. The latest sighting in 2015 was 73 days after tag deployment and nothing unusual was noted at that time. However, 321 days after tagging, this individual was photographed with the anterior portion of the tag showing at the surface of the skin (Fig. 6B and 6C). Close examination of the photograph revealed breakage of the welding joint (Fig. 6C), resulting in the separation of the anchor and the transmitter housing. The anchor was confirmed to have been shed some time between 326 and 346 days after deployment.

Remediation of design deficiencies (Phase 1)

The anchor articulation

The breakage of the articulation point observed in articulated tags (deployed in 2011) was resolved by welding the anterior and posterior sections of the anchoring system at the articulation joint (for anchors that had already been built, Fig. 2A) or by manufacturing new anchoring systems without the articulation joint. This led to the
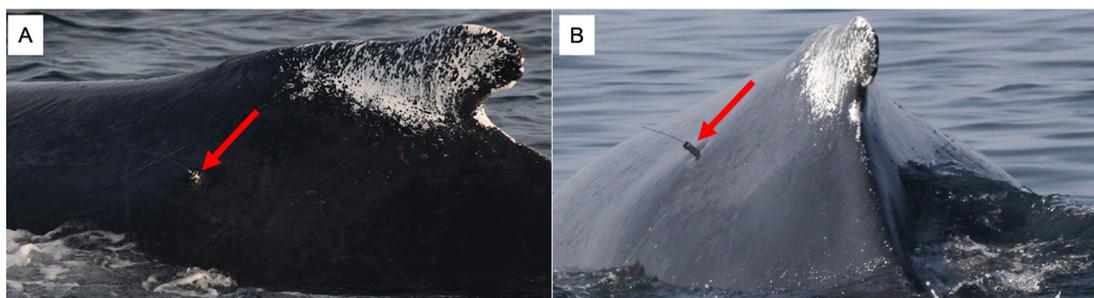

Figure 5: Consolidated tag (red arrow) deployed on a Gulf of Maine humpback whale that was not transmitting while still attached to the whale. A: last sighting with a functioning tag, day 31 after deployment; B: non-functioning tag on day 60 after deployment. The tag was seen on the whale up to day 79 after deployment, but no transmissions were received since day 46 after deployment.

Figure 6: Breakage of the welding joint on a welded SPOT-372 tag. A: tag on the day of deployment; B: tag site showing the broken tag 326 days after deployment; C: magnified version the broken tag showing the welding joint more clearly. Note also the forward bent petals. The broken tag was shed no more than 24 days after breakage was first documented.

discontinuation of the articulated tag in subsequent deployments (both in the GoM and elsewhere) and the development of the interfaced tag used during the 2012 season. No breakage of the anchoring system itself was documented after the articulation was eliminated.

The anchor-transmitter interface

Removing the articulation revealed another important deficiency in consolidated tags at the interface between the anchor and the transmitter housing. Both articulated and interfaced tags were equipped with this interface, but breakage at that location was not documented for articulated designs, likely because the failure of the articulation occurred first, which resulted in the loss of most of the tag components. Ultimately, the interface was eliminated by welding the anchor and the transmitter housing when the tag was manufactured (and before the electronic package was installed in the tag). Some tags had already been produced when breakage of the interface was first documented, and a temporary solution other than welding was implemented because the heat associated with welding could permanently damage the electronics. This temporary solution consisted of a reinforcement sleeve, which was installed to protect and strengthen the interface in the reinforced tags (Fig. 1C). Only three tags were deployed with this sleeve and no breakage was documented.

Possible damage to the 'epoxy bulb'

A design change was made to the posterior end of the tag to minimise the chances of damage to the epoxy that encapsulated the electronics (the epoxy bulb) and, potentially, the conductivity sensor and the antenna. The epoxy encapsulation was modified to be completely protected by the housing, resulting in a flat posterior end of the tag, with no epoxy projecting beyond the housing (Fig. 7). The conductivity sensor was also re-designed as a small, rigid wire adjacent to the antenna. This new design made the posterior end of the tag less vulnerable to damage by deployment devices (e.g., the tag carrier) and less exposed if contact with another individual or the sea floor occurred.

The anchor-transmitter housing welding joint

Addressing the breakage of the anchor-transmitter welding joint required more substantial testing of consolidated tags and remediation measures could only be implemented once experiments on Phase 2 of this study was conducted as described in Supplementary Material 2.

Phase 1 tag design

The SPOT-303 (Table 1, Fig. 1D, Supplementary Material 5, Fig. S18) resulted from remediation of most structural deficiencies described above. In this design, the anchor is attached to the tag housing via a welding joint. This tag includes a triangular tip with two blades, one set of actively deployed retention flaps near the tag tip and one set of 12 petals at the tag body. This tag is 300 mm long, 24 mm in diameter and weighs 390 g. The petals measure 50 mm in length, 5 mm in width and their thickness is 0.26 mm.
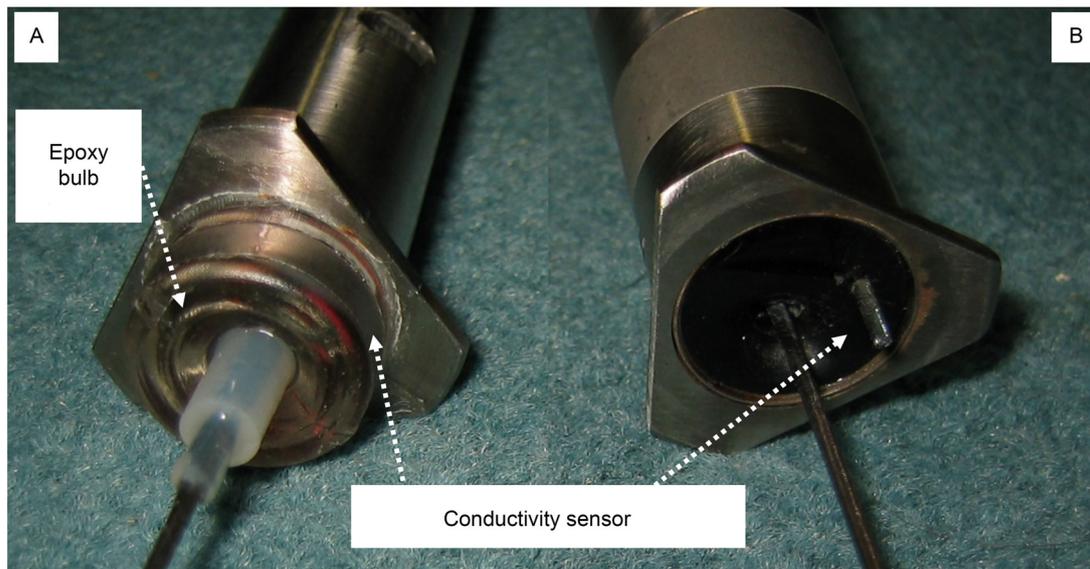
Figure 7: Posterior end of consolidated satellite tags showing changes to the epoxy, antenna and conductivity sensor. A: design showing the epoxy bulb projecting from the tag housing and the conductivity sensor represented by a metal ring around the bulb; B: new design showing a flat surface at the posterior end of the tag housing and the conductivity sensor represented by a small, rigid wire.

Development of a robust satellite tag (Phase 2)

Field observations revealed structural issues with the consolidated tags that needed to be addressed immediately as described in Phase 1. However, they also suggested the need for a more thorough re-evaluation of tag designs. Therefore, a series of laboratory experiments was developed to evaluate where improvements were needed, test their effectiveness, and develop the new tag design described below.

Tag anchor tip

Field observations using slow-motion video cameras and laboratory experiments suggested that the asymmetrical double bladed, triangular tip used in the articulated, interfaced, reinforced and SPOT-303 designs illustrated in Fig. 1 could lead to changes in the angle of penetration of the tag upon deployment (Supplementary Material 2, Fig. S9), potentially resulting in sub-optimal attachments (e.g., anchoring of the tag only in the blubber). Insertion tests of three different types of tips in the carcass of a minke whale (*Balaenoptera acutorostrata*) suggested that symmetrical pyramidal-shaped tip similar to that used in the darts of Low-Impact Minimum-Percutaneous Electronic Transmitter (LIMPET) tags (Andrews *et al.*, 2008) would facilitate tag penetration, require less deployment force, and present lower risk of changes in trajectory upon contact with the surface of the whale body (Supplementary Material 2, Fig. S7).

Tag retention elements

Laboratory experiments indicated that two primary changes were needed to improve the robustness and retention power of certain elements in the anchoring system: (1) replacement of the actively deployed flaps because of the potential for damage or breakage, and (2) strengthening of the petal elements to increase retention. The two actively deployed flaps of the original anchor design were held in place by a small horizontal pin near the tip of the tag. This pin was found to be prone to breakage (Supplementary Material 2, Fig. S10). Modification of the petal design was performed to improve robustness of the retention devices by changing the dimensions of the petals to make them stiffer, with potentially stronger retention power. In addition, the number of petal skirts was increased to replace the actively deployed flaps from earlier tag designs. All petal skirts were welded to the body of the tag and pull-out tests showed them to be robust (Supplementary Material 2, Fig. S11). The new sets of petal skirts were assembled in a staggered orientation on the tag to maximise retention (staggering allows for a greater surface of the petal skirts to engage with the surrounding tissue).

A new tag design

The new tag design produced by this study's Phase 2 was the SPOT-372 (Table 1, Fig. 1E, Supplementary Material 5, Fig. S19). The SPOT-372 design includes a grooved pyramidal shaped tip and three sets of retention petals. It is 293 mm in length, 24 mm in diameter and weighs 390 g. The retention petals measure 38 mm in length and 4.5 mm in width (Fig. 1E). The thickness of the first set of petals (closer to the tag tip) is 0.5 mm, while thickness for the second and third set of petals is 0.38 mm. This instrument was manufactured in two versions: one in which the anchoring system and the transmitter housing were welded (at the welding joint) before the electronics were installed (the SPOT-372-welded version) and another where the entire tag was produced using 3-D printing techniques (the SPOT-372-DMLS version). These two tag versions are identical in their anchor design, dimensions and weight; the only difference is the process by which they were manufactured. Given the breakage of the welding joint described in the previous section, the SPOT-372-welded, which was only deployed in 2015 on humpback whales in the GoM, was discontinued. The SPOT-372-DMLS is the most robust design of consolidated tag currently available for deployment in large whales.

Assessment of tag transmission duration and tag egress

The five tags described above (Fig. 1, Table 1) were pooled into two broader categories for statistical analysis due to the relatively small sample sizes for some designs. Tags with more prevalent design deficiencies, including the articulated anchor ('articulated' tags, Fig. 1A) and with anchor-transmitter interfaces connected via a threaded pin ('interfaced' tags, Fig. 1B) were categorised as 'non-integrated'. Tag in which design deficiencies were addressed (e.g., articulations or anchor-transmitter interfaces were reinforced by a sleeve ['reinforced tags', Fig. 1C], were welded or were removed by manufacturing the tag as a single unit ['SPOT-303,' Fig. 1D, and 'SPOT-372,' Fig. 1E]) were categorised as 'integrated' (Table 1). Attachment duration for non-integrated and integrated tags is summarised in Table 3. Mean and median durations were, respectively, 28.8 and 21 days for non-integrated tags and 47.5 and 38.5 days for integrated tags. These results show an increase of 65–85% in tag transmission duration for the more robust, integrated tag designs (Fig. 8). The most parsimonious GLM to assess tag duration included the following variables: tag category, vertical placement, and penetration depth on deployment (Table 4). Model outputs indicate that transmission duration was significantly longer for integrated tags, for tags deployed high on the body, and for tags that are less protruded at the time of deployment.

Integrated tags deployed in 2013 and 2015 were used to assess normal (i.e., not related to tag breakages) tag egress. Twenty individuals were resighted on at least one subsequent day while the tag was still attached,
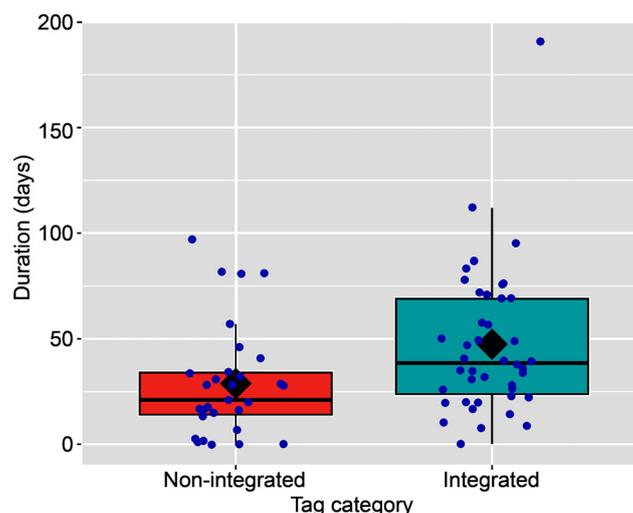

Figure 8: Tag duration of non-integrated and integrated consolidated tags deployed on Gulf of Maine humpback whales. The black diamond and the boxplot horizontal black line represent the mean and median tag duration, and the blue dots correspond to individual tag durations; see also Table 3.
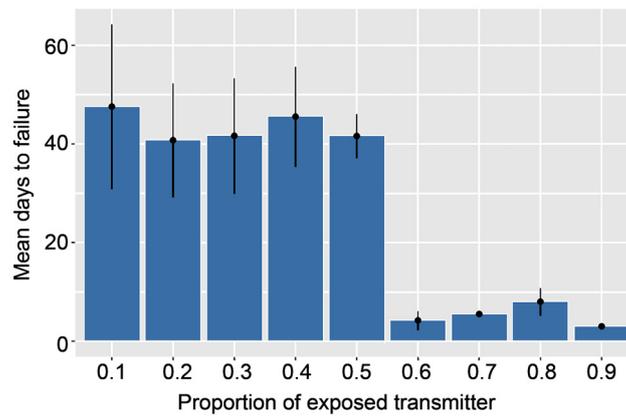
Figure 9: Mean time to failure versus transmitter housing exposure. Transmission duration was significantly lower when the transmitter was exposed by more than half of its length. Values indicate the proportion of the tag housing exposed and the error bar depicts the standard deviation.

Table 3

Summary of transmission duration (in days) for non-integrated and integrated satellite tags deployed on Gulf of Maine humpback whales

Tag Category	n	Mean	Median	SD	Min	Max
Non-integrated	31	28.8	21	26.3	0	97
Integrated	42	47.5	38.5	34.8	0	191

Table 4

Model parameter estimates for the most parsimonious generalized linear model to assess tag transmission duration for satellite tags deployed on Gulf of Maine humpback whales

Model Coefficient	Estimate	SE	*t*-value	*p*-value
Intercept	−0.422	0.902	−0.468	0.641
Tag Category (Integrated)	1.266	0.413	3.068	**0.003**
Circumferential position (Dorsal)	0.924	0.401	2.303	**0.024**
Penetration depth	0.010	0.004	2.748	**0.008**

and the degree of egress could be reliably determined. On average, these observations occurred on 5.6 days per whale (range = 2–17). Transmission duration exceeded 40 days for tags implanted more than 50% of their length. However, once approximately half or more of the transmitter housing was exposed, the time to failure decreased by an order of magnitude (Fig. 9). Only six tags of all instruments deployed in 2013 and 2015 were observed still on the whale in a subsequent sighting after more than half of the transmitter was observed outside of the body.

There were, nevertheless, cases of abrupt tag egress when the instrument was still well implanted. For example, the tag of one individual that was only approximately 20% exposed on Day 13 after deployment. Two days later, it had egressed to 70% exposure and the tag was shed five days later (Supplementary Material 7, Fig. S20). As another example, one tag was less than 40% exposed on Day 30, yet transmission ceased the following day. However, in that case, it was not possible to resight this whale until 45 days after deployment to visually confirm that the tag had been shed.

DISCUSSION

Structural tag design deficiencies

The most significant outcome of this study was a considerable improvement to the retention of satellite tags for baleen whales together with the reduction of health impacts to the tagged whales (see also Gulland *et al.* (2024) for an assessment of the physical effects of the tags described in this study). Typically, satellite tags stop

transmitting before their battery life ends, but the specific cause is rarely known. There is a range of possible causes of premature transmission reception cessation, including failures in the electronics package or the attachment system and trauma to or removal of the tag after deployment. Here, intensive follow-up effort was employed to document the status of the tag and/or tag parts attached to the whale, revealing that early consolidated tag designs (articulated or interfaced) were not sufficiently robust to withstand forces during and/or after deployment. As such, tag breakage was one of the primary reasons for the shorter duration of these tags.

Improvements to the tag design and manufacturing were initially implemented in the most logistically straightforward and expedient way to allow for deployment of existing tags while still reducing risks to whales. One example of these improvements included eliminating the articulation by welding the two sections of the anchoring system on each side of the braided cable. This was relatively easy and inexpensive to implement, but the potential for shearing at the muscle/blubber interface (e.g., Moore *et al.*, 2013) suggests that an articulated anchor could be beneficial in minimising tissue trauma and, at least in theory, improving tag retention. The articulation used in this study was a single point one, which would only compensate for shearing forces if the articulation were located at the right level at the muscle-blubber interface. If the articulation was located above or below the fascia, it most likely would not be able to compensate for shearing. The implementation of multi-articulated or fully flexible anchoring systems would likely result in greater probability that the implanted components are better able to accommodate the shearing forces, which could lead to lower impacts to the whale and longer attachment durations. However, the trade-off between developing more complex anchors and the likelihood that additional complexity could introduce new unexpected design deficiencies must be carefully evaluated. The forces that these tags are subjected to once they are deployed are still poorly known (as this study has demonstrated). Therefore, additional data are needed to inform the design of anchor articulations in subsequent tag designs. In addition, it would be important to consider whether developing a more complex anchoring system would result in improved tag retention and would minimise the risks to the animals. Results of this study showed that completely rigid tags (such as the SPOT-303 and SPOT-372, fully integrated tags) can improve the functional life of the tag and can result in relatively minor observable effects (behavioural, tissue response and otherwise) if the tags are deployed in areas of the body where the risk of health effects to the animals appear to be lower (Gulland *et al.*, 2024). Therefore, the implementation of articulated anchors, while potentially beneficial, must be carefully considered in the future.

One of the deficient components identified in this study, the anchor-transmitter interface, has been common to various tag designs used to track large whales for at least 25 years (e.g., Wade *et al.*, 2006; Zerbini *et al.*, 2006; 2011; 2018; Mate *et al.*, 2007; 2011; Dalla Rosa *et al.*, 2008; Gales *et al.*, 2009; Gales *et al.*, 2010; Hauser *et al.*, 2010; Citta *et al.*, 2012; Guzman *et al.*, 2013; Heide-Jørgensen *et al.*, 2012; Prieto *et al.*, 2014) and the separation of anchors from the tag has also been observed in blue and gray whales (Gendron *et al.*, 2015; Goley *et al.*, 2024). It is likely that breakage and/or bending at that interface (with consequential tag failure) has been a common event that has not been previously identified because follow-up studies were limited, with insufficient temporal resolution to observe tag damage. This could, at least in part, explain the relatively short duration of many satellite tag designs used with large whales to date.

It is unclear whether the modification of the posterior end of the tag with the full protection of the epoxy-encapsulated electronics resulted in improvement in tag duration. This change in design was implemented along with the removal of the anchor-transmitter interface, and so it is not possible to unequivocally attribute improvements to one or the other tag modification. However, it is likely that the integration of the anchor and transmitter played a greater role in this study, given that the incidence of breakage at that interface had been documented more often. In fact, damage to exposed epoxy was only suspected, but not confirmed, for one of the tags deployed in the GoM. While this study partly motivated the re-design of the posterior end of the tag, most of the evidence of the weakness of exposed epoxy came from opportunistic observations of humpback whales tagged in other regions. This provided definitive evidence of the potential weakness and sufficient justification to develop an alternate design for that section of the tag. Although this problem appeared to be of less significance in the GoM, follow-up monitoring of animals with a newly designed tag posterior end nevertheless provided evidence that the new design appeared to be robust.

It was not possible to evaluate the influence of the modifications to the tip of the anchor design and retention elements because they occurred simultaneously. Furthermore, sample sizes were too small for a rigorous statistical analysis that must consider all factors affecting tag duration. In addition, it was difficult to document the state of the retention petal skirts in the field because it is expected that tags fall off at the same time as the petals become exposed. However, photographic documentation of the third petal row of one SPOT-372 tag 322 days after tag deployment showed that no breakage had occurred, and the petals were bent forward in a similar fashion to that documented during the slow speed removal experiments in hard durometer rubber (Supplementary Material 3, Fig. S13). This suggests that the removal experiments described above may be appropriate to reproduce, at least in part, the forces and conditions to which petal skirts are subject during the period when a tag remains attached and as the tag egress out of the whale's body.

Even though multiple tag structural deficiencies were identified in this study, the specific causes of breakage remain unknown. The anchor articulation most likely broke as a result of the failure of the stop sleeves or the braided cable responsible for providing flexibility at the articulation point. These parts could have failed on deployment or from pressures exerted on the tag after attachment or during its outward migration. In the case of the anchor-transmitter interface, separation could theoretically have resulted from the transmitter unscrewing from the anchor over time (e.g., if the metal glue or epoxy were not properly applied or if proper bonding did not occur), resulting in a gap between the two tag components and facilitating bending or breakage of the threaded pin or separation of the anchor and the transmitter. However, this study produced multiple re-sightings of whales where the interface broke or bent, with no evidence that the tag had rotated (i.e., unscrewed) over time (Supplemental Material 3). Breakage of the anchor/transmitter interface was more likely caused by contact between the tagged whale and objects in the environment, the sea floor or a conspecific, particularly when the interface was exposed due to tag egress.

New tag features

Two new features were introduced in this study to improve inference about tag egress: (1) a light sensor on the communication port of the tag; and (2) standard-interval etchings on the transmitter housing. The light sensor was developed as a tool to remotely estimate tag egress. More details on this feature, as well as validation of the light sensor data, is provided in Kennedy *et al.* (2024). The etchings placed on the transmitter housing (Fig. 1B, D and E) provided an accurate method to estimate tag egress from photographs. Although they were initially limited to the upper 3.5 cm of the posterior end of the tag (Kennedy *et al.*, 2024), they were subsequently extended along the entire transmitter housing and could be reliably viewed across a wide range of angles and photo-quality. Even when finer detail on tag egress was sought through photogrammetry (as described in Gulland *et al*., 2024), the etched markings still provided valuable information to then scale photographs for those measurements. Etched housings would therefore be valuable to any project in which observers might encounter and photograph the whale after tagging.

Tag egress

Humpback whales were particularly suitable for this study because the mean tag deployment duration for this species can be 2–3 times lower than other large whales for the same type of tag and deployment method (Mate *et al*., 2007, Fig. 5). Prior to this study, there had been few insights into the cause of those short deployment durations and the specifics of tag egress from the body. This study generated a large dataset to evaluate tag egress in relation to transmission failure. However, the cessation of transmissions for many tags was thought to be due to tag breakage, versus the normal process of tag rejection from the body. Nevertheless, it appears that integrated tags continued transmitting until a relatively large portion of the instrument was exposed. It was also noteworthy that anchors without an attached transmitter persisted in the body for up to four years but still ultimately shed from the body in cases where retention time of broken anchors could be assessed. Thus, external forces, such as drag, do not appear to be needed for a tag part to ultimately be rejected.

Results obtained from tag egress and the status of anchors post-breakage could be informative for future development of consolidated tags. For example, new designs could be built to compensate forces applied to the

tag when exposure reaches 50% of the transmitter housing to minimise the rate of tag loss over time and, consequently, improve tag duration.

Current tag design

At the time of publication of this study (July 2025), both SPOT-303 and SPOT-372-DMLS designs were commercially available from a tag manufacturer.[12] Based on the experiments conducted here, the tag housing and anchoring elements of the SPOT-303 may not be as robust as the SPOT-372. Therefore, the latter is recommended for deployments in large whales. This is particularly important if the target species is known to experience high rates of conspecific physical interactions. Nevertheless, these two tag designs have been used in multiple species of large cetaceans in various oceans (e.g., Vogel *et al.*, 2023; Kennedy *et al.*, 2024; Landine *et al.*, 2024; Vermeulen *et al.*, 2024). To date, no breakage of tag elements and no new design deficiencies have been observed when systematic or opportunistic follow-up data from tagged whales were obtained (e.g., Zerbini *et al.*, 2023).

Even though the mechanical elements of these tags (anchor, transmitter housing and retention elements) were evaluated or developed through this study for location-only (Wildlife Computers SPOT) tags, data archiving tags (SPLASH10-302 and SPLASH10-373)[12] have also been introduced with a consolidated design of the same dimensions as the SPOT tags.

Tag retention

As expected, statistical analysis provided quantitative evidence that correcting major design weaknesses in the non-integrated tags (articulated and interfaced designs) significantly increased tag duration. They also indicated that the proportion of the tag exposed at the time of deployment was negatively correlated with tag duration and that tag deployment higher on the body of the whale was positively correlated with transmission duration. One of the advantages of consolidated tags when compared to other types of cetacean satellite tags (e.g., type A or anchored tags, Andrews *et al.*, 2019) is that they are designed to fully implant into the body, leaving only the antenna and the conductivity sensor (or saltwater switch) exposed. Fully implanted, consolidated tags likely cause less drag at the surface of the skin than partially implanted tags (Mate *et al.*, 2007) and reduce the chances of tags being removed by contact with conspecifics. Therefore, as shown by the statistical analysis provided here, full implantation results in longer transmission duration. Furthermore, greater transmission duration of tags deployed higher on the body is expected because stiffer tissue in that region of the body may provide better anchoring for fully implanted tags and because the potential tissue trauma due to shearing forces at the muscle-blubber interface (Moore *et al.*, 2013) is substantially reduced when compared to lower (more ventral) areas of the flank of the whales (e.g., Moore & Zerbini, 2017).

Because of relatively small samples, the tag designs evaluated in this study were pooled into two categories: non-integrated and integrated. The two integrated tags currently available (SPOT-303 and SPOT-372) have different retention elements and, therefore, their retention times may differ. Further studies are needed to assess duration transmission across these two designs, although preliminary data suggest that the SPOT-372 provides longer attachment duration than the SPOT-303, at least for humpback whales, blue whales (*B. musculus*) and southern right whales (*Eubalaena australis*) (Zerbini *et al*., 2023).

Failure of the electronic components has been proposed as one potential explanation for the relatively short transmission duration of consolidated satellite tags. While this may have been the case in the past, the electronic tag components of the SPOT satellite tags used in this study appeared to be reliable. All but one of the tags deployed in humpback whales in the GoM operated as programmed and tags were shed when whales relocated after transmissions stopped. In only one case, the tag was still properly attached but not transmitting.

Importance of follow-up studies for tag development

This study demonstrates the importance of follow-up of tagged individuals to assess performance and shortcomings in tagging technology and understand tag effects on individual whales (see also Gulland *et al.*,

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[12] *https://wildlifecomputers.com/taxa/cetacean-transdermal/*

2024; Robbins *et al.*, in prep, a and b). Photographic and video documentation of tagged whales can be an effective way to monitor the condition of satellite tags, the rates of egress and the conditions of the tag site. The sequential observation of tagged whales allowed for documentation of tag design flaws and for those flaws to be corrected, which resulted in improved transmission duration of satellite tags and reduced adverse health effects caused by tag parts breaking and/or remaining attached with no on-going scientific purpose (Gulland *et al.*, 2024). Humpback whales in the GoM were ideal for this follow-up study because of their high site fidelity and the high sighting rate. While the level of observer effort may be difficult to replicate in other areas, the data collection methods used in this study can be easily extended to other species and populations.

Both dummy and actual versions of the initial satellite tag designs used in this study had previously undergone laboratory tests to assess their robustness (Gales, unpublished data). For example, tags were fired onto layers of foam and rubber matting, into whale carcasses, or sections of whale blubber. They were also pressure tested and examined under computerised tomography scans to assess potential damage after impact and pressure testing. While these tests led to various improvements, they were likely not representative of conditions in the field. Only after tags were deployed on whales and these individuals were closely observed, important inadequacies in the robustness of the tags were revealed. This confirms that, while laboratory testing must be an integral part of satellite tag development, it is difficult to reproduce the conditions that these devices are subject to in the field, especially when the forces on the tag attached to the whales remain unknown and likely dependent on many factors, including species, time of year, tag penetration depth and location on the body after deployment.

The results presented here provide unique and detailed evaluations of consolidated catacean tag designs used in large whale tracking during the past several decades. The identification of structural deficiencies with subsequent improvements in tag robustness, tag functional life and in the welfare of tagged animals (Gulland *et al.,* 2024) are clear indications that follow-up studies are an essential component of any tag development effort, especially when development involves invasive techniques. Assessment of technology through these types of studies will likely make development more efficient, less expensive and less likely to affect the health of tagged individuals.

ACKNOWLEDGEMENTS

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Supplementary material

SUPPLEMENTARY MATERIAL 1

Schematics design of transmitter SPOT-193J used in the first deployments of consolidated tags on Gulf of Maine humpback whales
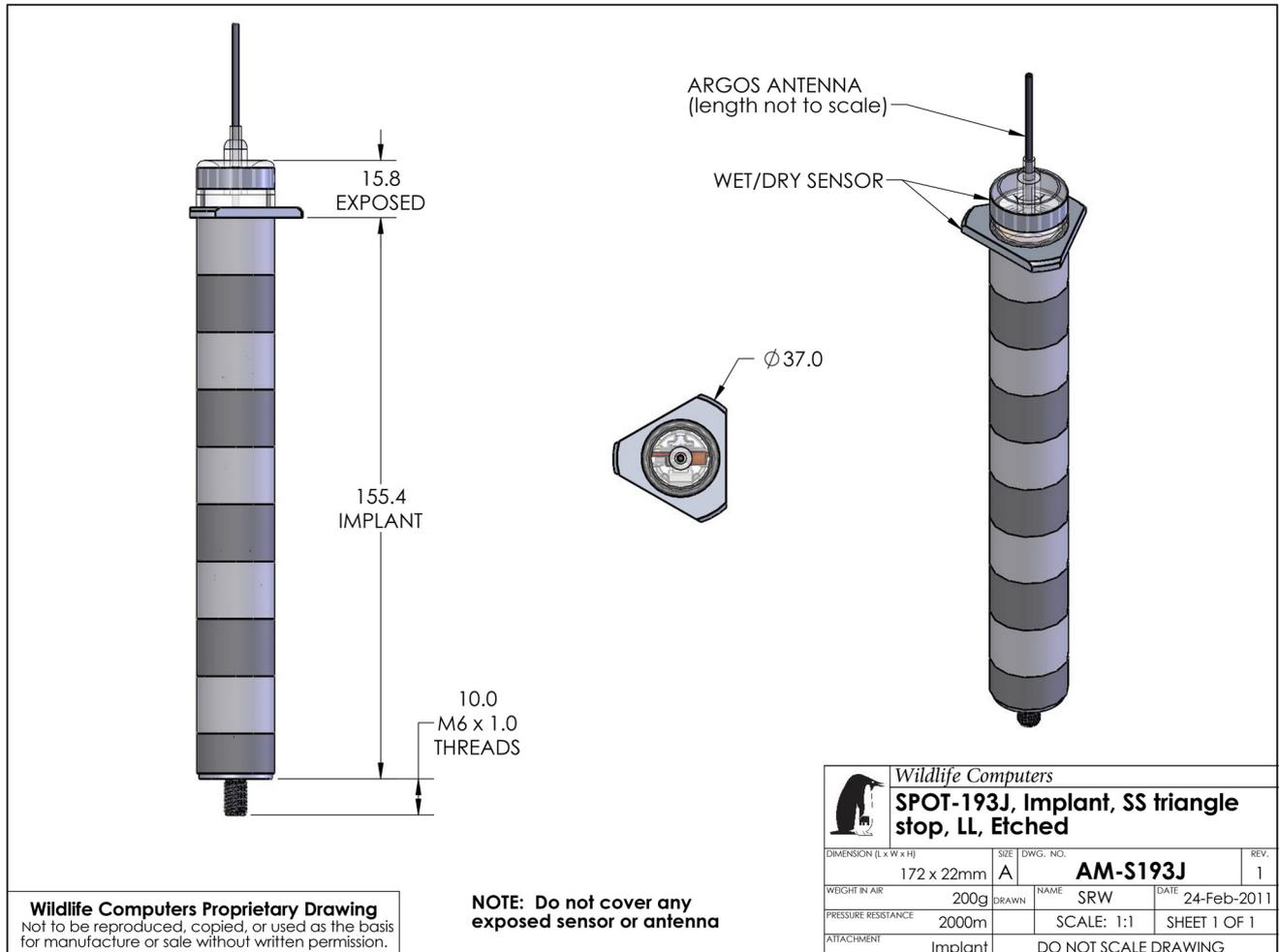

Figure S1: Schematics of the housing of the SPOT tag used in the articulated, interfaced and reinforced satellite tags deployed in the present study. Note the hatched rings of equal height designed to assess the rate of migration of the tag in or out of the tag insertion site after deployment.

SUPPLEMENTARY MATERIAL 2

Laboratory experiments to assess consolidated satellite tag robustness

As described above, structural improvements in tag anchoring systems and transmitter housing occurred in two phases. As part of Phase 2, several experiments were conducted to assess the strength of the tag elements to better inform tag design and assess the potential for mechanical failures in new tag features. These experiments are described below.

Dolphin oscillator

Experiments to evaluate shearing at the muscle-blubber interface and consequential trauma caused by intramuscular implantable tags were conducted in the laboratory at the Woods Hole Oceanographic Institution. These experiments were also used to assess robustness of elements of the anchoring system.

The methods and results of these experiments are presented in detail in Moore & Zerbini (2017). Briefly, scaled, intramuscular dummy tags were modelled after full size large-whale satellite transmitters (Fig. S2) assuming a scaling factor of 1/7 (that is, to scale a consolidated tag for a 14 m long humpback whale to a 2 m long dolphin).

Figure S2: Consolidated satellite tag and 1/7th scaled dolphin dummy tag. Inset shows dummy at a larger scale (scales in cm) (reproduced from Moore & Zerbini, 2017, p. 3720).

These miniaturised dummy tags were designed with a retention element (a retention flap) like those seen in the anchoring system of the tags used at the time (e.g., articulated, interfaced, reinforced and integrated SPOT-303). Dummy tags were inserted into the blubber and muscle on the dorsal midline and right dorsolateral side of common dolphin (*Delphinus delphis*) carcasses at nine stations that are exposed to the air during normal cetacean swimming (Fig. S3).

Figure S3: Location of scaled tag insertions in dolphin cadavers during experiments to assess shearing and tissue trauma associated with tag implantation. Stations were labelled 'A' through 'I'. Station A is in the dorsal midline anterior to the dorsal fin (arrow). Stations B, D, F and H were the upper lateral line as shown in the figure, and stations C, E, G and I the lower lateral line. Note that miniature tags shown in Fig. S2 are inserted in the dolphin cadaver (reproduced from Moore & Zerbini, 2017, p. 3718).
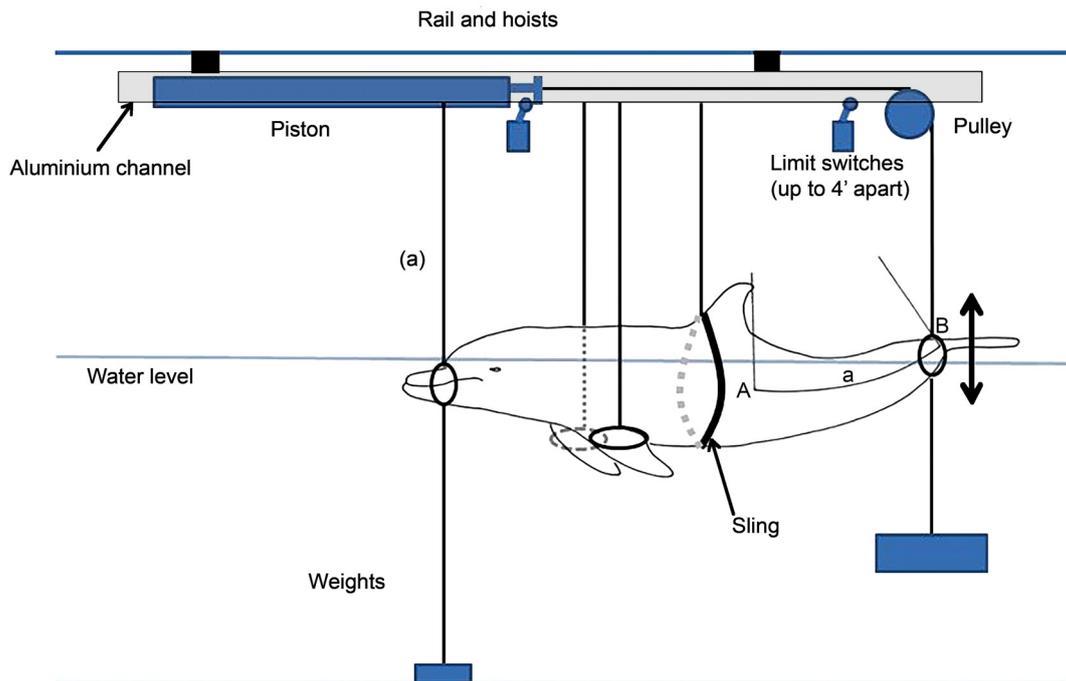
Figure S4: Experimental system for repeated oscillation of dolphin cadaver (reproduced from Moore & Zerbini, 2017, p. 3720).

A reciprocating oscillator (Fig. S4) was fabricated to mimic swimming movements. The cadavers were suspended in a water tank and their peduncle was moved by the oscillator for 18–24 hours. Subsequently, each tag site was excised and dissected. The extent to which the retention features had deployed and the orientation of the tip were recorded, and the height and width of any cavity present around the tag were measured. The oscillator experiments suggested that the horizontal pin holding the retention blade to the anchoring system was prone to breakage and consequential separation from the tag (Fig. S5), resulting in metal parts of the tag being left in the body of tagged whales.

Assessment of penetration and removal forces on scaled tags

Penetration and retention power of the tip and retention devices were evaluated through insertion (push-in) and removal (pull-out) experiments of six different miniature tag designs (Table S1, Fig. S6, left) in the carcass of a minke whale (*Balaenoptera acutorostrata*). These miniature tags mimicked existing tag design tips and retention elements for different types of body-penetrating tags with both dermal and sub-dermal attachments (e.g., Andrews *et al*., 2008; Gales *et al*., 2009; Baumgartner *et al*., 2015). Insertion/removal experiments of real size tags were also conducted in hard durometer, rubber materials and in humpback whale tissue.

A load cell (Fig. S6, right) was used to measure forces required to insert and remove the miniature tags from the minke whale cadaver. The experiment was repeated three times for each tag type and the maximum forces were recorded when tags were pushed in and pulled out. In addition to the required forces to insert and remove the miniature designs, possible breakage in retention elements were documented as they could inform design of new consolidated satellite tags.

The experiment on the minke whale cadaver indicated a symmetrical, three-bladed tip would be less likely to show changes in direction and would require less deployment power (less force) upon penetration. Fig. S7 illustrates results of the insertion experiment on minke whale tissue. The three-bladed tip anchor with retention elements (tag type F) would require substantially less force upon deployment than any other design equipped with similar elements (e.g., compare maximum forces for tag type F with types C, D and E). Maximum forces measured for type F was similar to those required to implant tags without retention elements (types A and B). Less force upon deployment is deemed as beneficial because it would allow tag deployment to be performed at lower pressures and, as a consequence, minimise tissue trauma upon impact of the tag and the tag carrier with the whale's body.
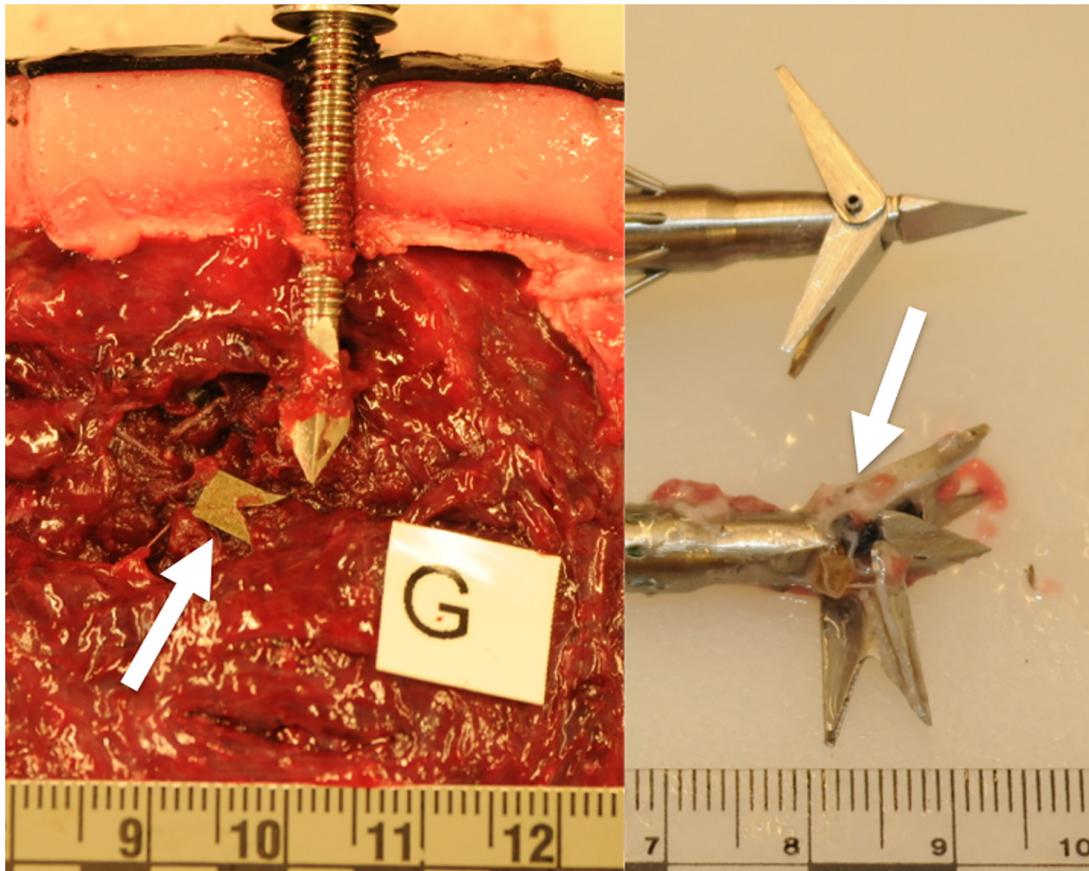
Figure S5: Breakage/separation of the retention blade (white arrows) from the tag anchor after the oscillator experiment on common dolphins (left) and the insertion/removal experiments on a minke whale carcass (right) using scaled tags.
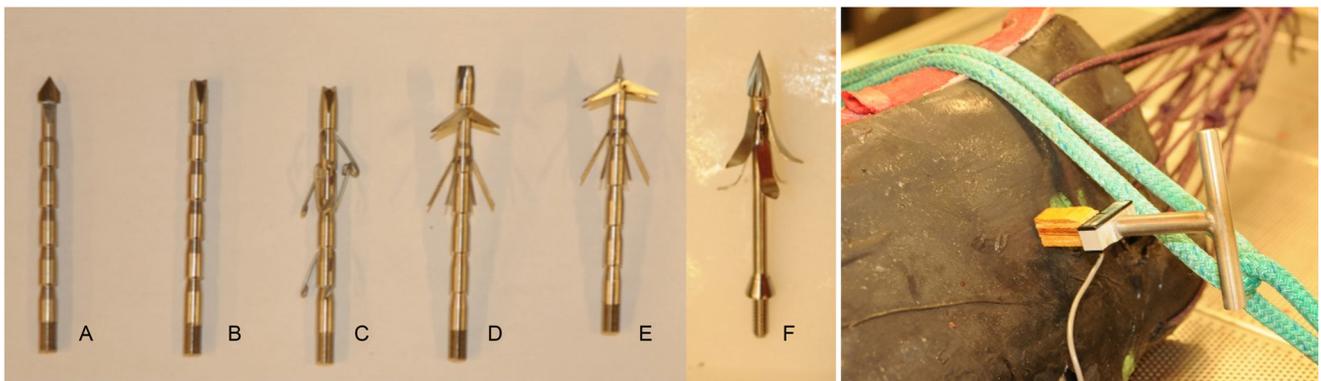

Figure S6: Miniature designs of potential satellite tag tips and retention elements used in insertion and removal experiments (types A to F described in Table S1) (left) and load cell with miniature tag inserted on a minke whale carcass (right).

Experiments in hard durometer rubber

The development of robust consolidated tag designs was also informed by laboratory experiments conducted with hard durometer neoprene rubber (40 to 80 A hardness) with full size tag designs. These included firing tags at perpendicular and acute angles using a pneumatic rifle (Heide-Jørgensen *et al.*, 2001) at close range (1–2 m) and at higher pressure (25 bar) (Fig. S8) than those typically used in the deployment of consolidated tags in free ranging animals (7–18 bar). The goal here was to evaluate cutting power of the tip designs and potential changes in angle of penetration of the tag tip. They also included insertion and removal tests (Fig. S8) at either high speed (to simulate and abrupt removal of the tag) or low speed (as an attempt to simulate forces applied during the

Table S1

Miniature tag designs used in experiments to assess penetration forces required to insert tags in cetacean tissue. Tag types referred to in the table are illustrated in Fig. S6

| Miniature tag type	Tip design	Retention devices	Observations
A	Two bladed, asymmetrical	None	Tip design of tag illustrated in Fig. 1
B	Four cutting blades arranged as a cross with side vents	None	Tip design equivalent to needle designs in Baumgartner *et al.* (2015)
C	Four cutting blades arranged as a cross with side vents	Loosely attached wires that can spin in all directions	Tip and retention elements equivalent to one of the needle designs in Baumgartner *et al.* (2015)
D	Four cutting blades arranged as a cross with side vents	Consistent with the design of Gales *et al.* (2009) shown in Fig. 1A	Design of the petals and flaps were different from original transdermal in order to accommodate miniaturisations
E	Two bladed, asymmetrical	Consistent with the design of Gales *et al.* (2009) shown in Fig. 1A	Design of the petals and flaps were different from original transdermal in order to accommodate miniaturisations
F	Three bladed, symmetrical	Two sets of petals (3 per row), staggered	Equivalent to LIMPET tag darts (Andrews *et al.*, 2008)
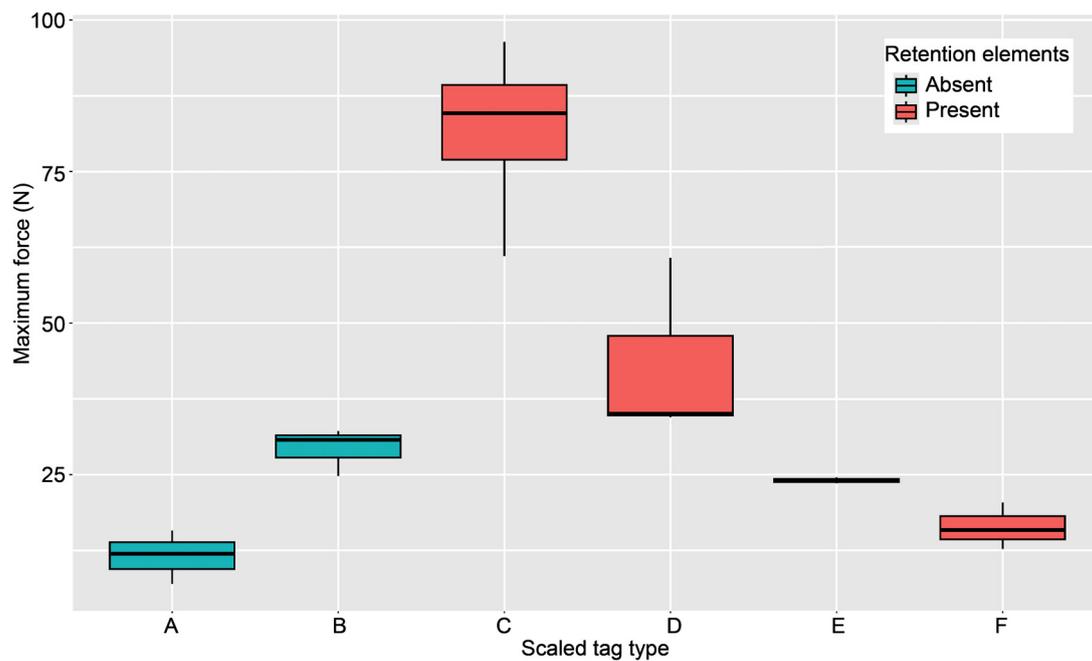
Figure S7: Boxplot of measurement of maximum force (N) required to insert scaled tags in cetacean tissue. Miniature tag configuration is described in Table S1 and illustrated in Fig. S6.

natural foreign body rejection process of the tag). These push-in/pull-out experiments were designed to assess the robustness of different types of retention elements upon penetration as well as removal of the tag, including the welding joints used to attach the petal skirts to the body of the transmitter and strength of the petals themselves.

Experiments in hard durometer material suggested the following:

1. The asymmetrical double-bladed tip could lead to changes in the angle of penetration of the tag upon deployment, potentially resulting in sub-optimal penetration and attachment of the tag. In contrast, the symmetrical three-bladed design is less likely to show changes in direction (Fig. S9).

2. Consistent with the insertion experiment in the minke whale carcass described above, the three-bladed tip penetrated deeper than the two-blade triangular tip design (Fig. S9).

Figure S8: Experiments to assess tag robustness in hard-durometer neoprene rubber (left: firing of tag designs with a pneumatic rifle; right: insert and removal of tags in a laboratory setting).

Figure S9: Angle of penetration of large whale consolidated satellite tags with asymmetrical, two-bladed tips (background) and symmetrical, three-bladed tips (foreground). This figure represents two different firing trials. Note the wider angle of penetration of two bladed tip tag in both trials.

3.   Pull-out experiments showed that the horizonal pin holding the actively deployed blades used in early tag designs was prone to breakage and consequent separation of the tip and the blades from the body of the tag upon deployment or by abrupt removal of the tag (Fig. S10).

4.   The passively deployed retention elements (or petals) were robust. No breakage was documented upon firing in hard durometer material or during removal experiments (Fig. S11).

Deployment of full-size tags in cetacean tissue

Full size tags were also deployed in actual cetacean tissue to assess whether penetration occurs as expected and retention elements behaved as designed (e.g., the retention elements anchor at the correct tissue layers). Real size tags were deployed vertically in humpback whale tissue using the same methods and deployment pressures as those typically used in field conditions. These deployments suggested that tags penetrated past the blubber-muscle interface and that the retention elements engaged into the connective tissue layer between these two tissue layers (the fascia) (Fig. S12).

Izod style and static tests

Field observations revealed that welding joints used to replace the mechanical interface between the anchoring systems and the housing of the electronics in the SPOT-372 tag design could fail (Fig. S13). Therefore, a new manufacturing process was used to remove the welding interface and produce the tag housing and anchor as a single unit: DMLS (Direct Metal Laser Sintering). DMLS corresponds to a three-dimensional (3-D) metal printing

Figure S10: Actively deployed blades mounted on a tag anchor (orange arrow) and the horizontal pin (red arrow) used to attach the blades to the anchoring system (left). Documentation of breakage of the horizontal pin (white arrow) after impact and pull-out tests on hard-durometer rubber, resulting in separation of the tip and retention blades from the shaft of the anchor.
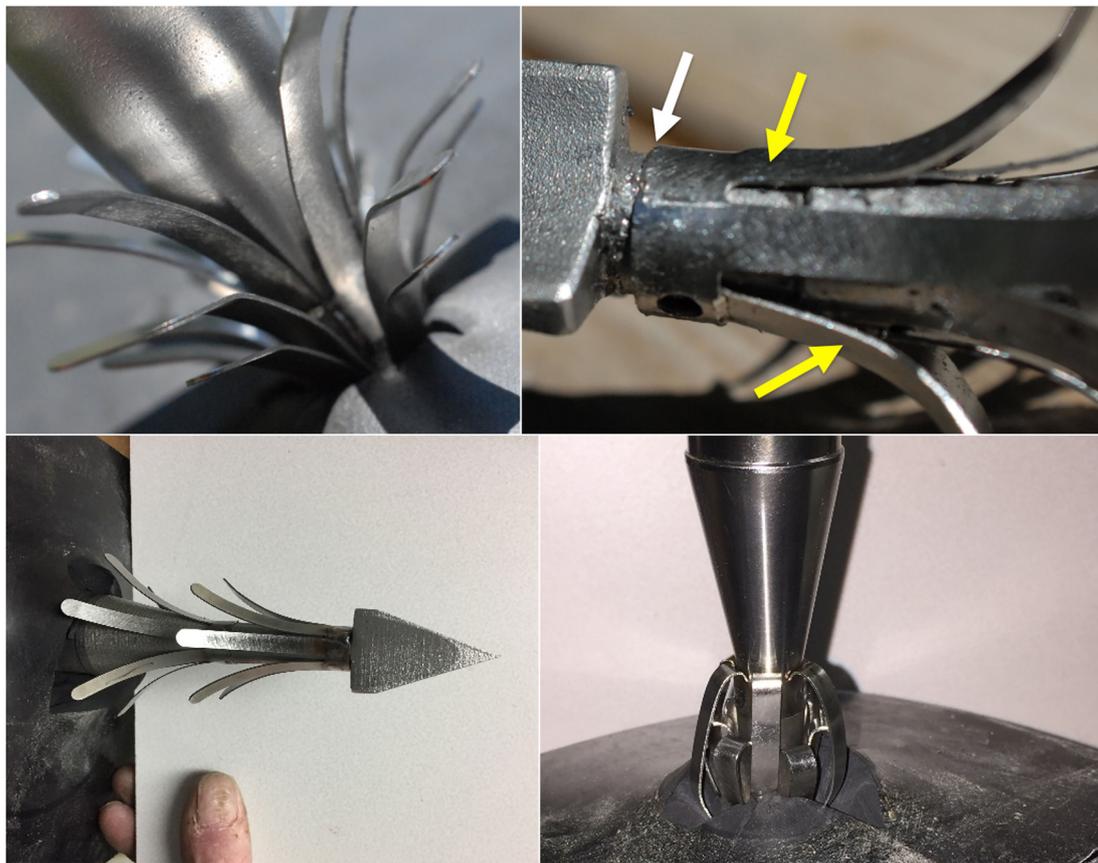

Figure S11: Impact tests to assess petal skirt welding and petal strength. Top left: Intact petal skirts deployed on hard durometer rubber with a pneumatic rifle. Top right: Detail of the petal skirt welding joint (while arrow) and the petals (yellow arrows) upon penetration through hard durometer rubber after high-speed deployment with a pneumatic rifle. Bottom left: Intact petal skirts after low-speed insertion experiment through neoprene rubber. Bottom right: bent (but not broken) petal set during a pull-out exercise.

technique developed in the mid-1990s. It has been increasingly used in prototyping metal structures, particularly stainless steel and titanium. This manufacturing process uses a high power-density laser to melt and fuse metallic powders together and has the ability to fully melt metal material into solid three-dimensional parts. An advantage of the DMLS method is that the manufacture of the tag housing can be done in a more consistent way and that it allows for a more uniform distribution of material strength across the length of the tag.
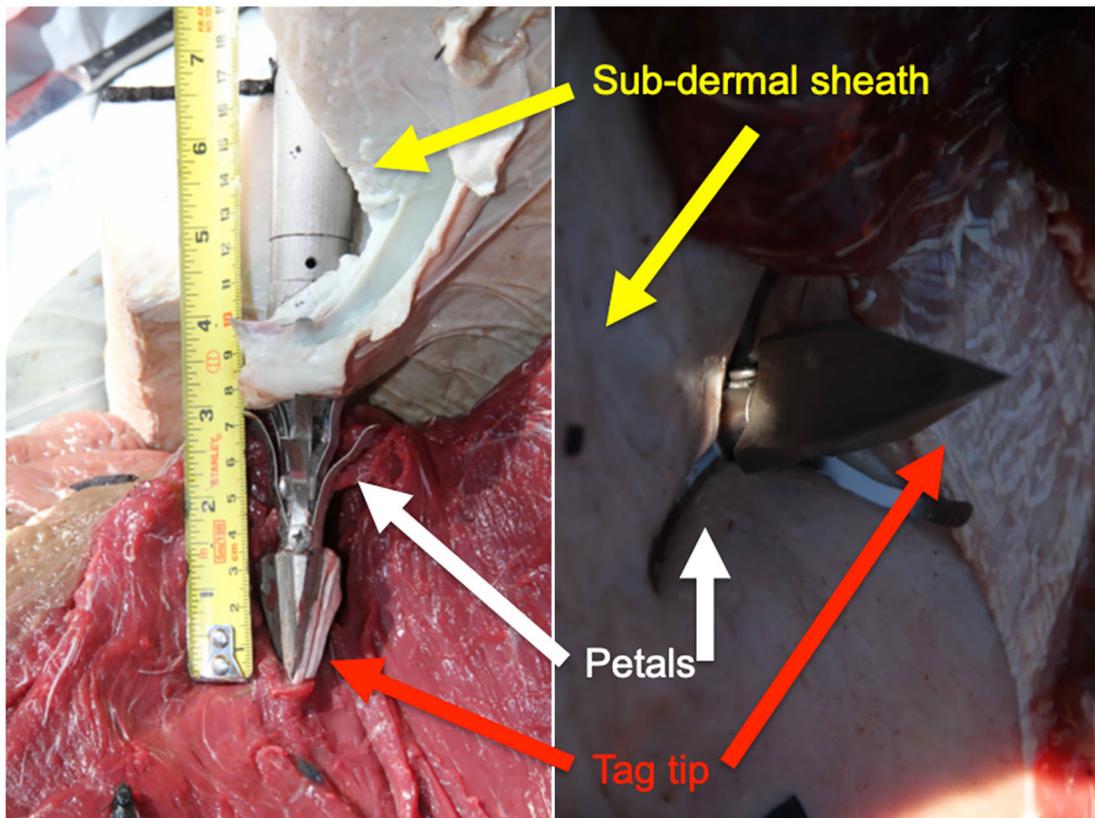
Figure S12: Deployment of a large cetacean satellite tag in whale tissue showing proper engagement of the petals to the sub-dermal sheath.
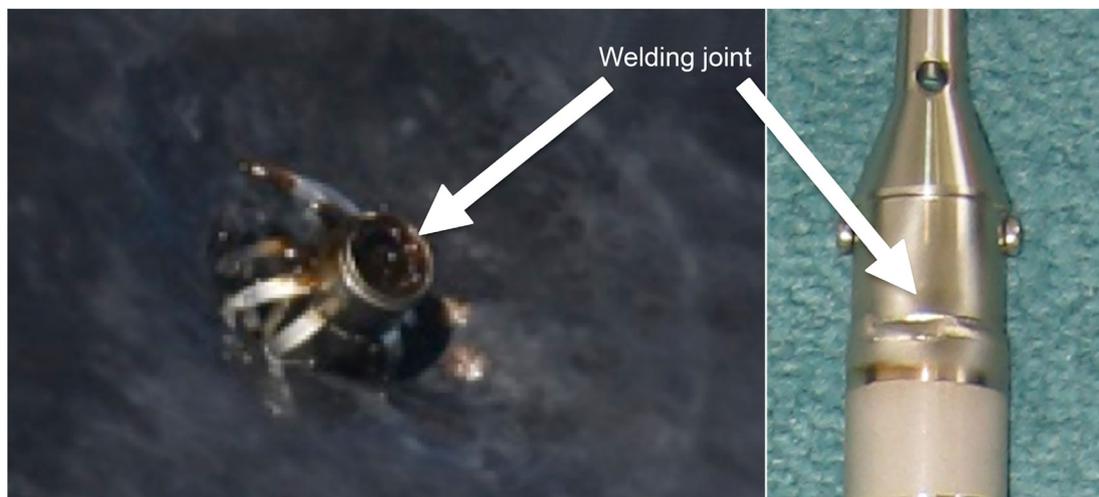

Figure S13: Photographic documentation of breakage of the welding joint between the transmitter and the anchoring system in the welded SPOT-372 design (breakage was documented 322 days after tag deployment). Note the petal bending forward in the left panel showing consistent pattern observed during laboratory removal experiments.

Izod style and static tests were used to assess the robustness of the DMLS design in comparison with tags in which the anchor and transmitter interface was welded (e.g., the first SPOT-372 designs). Izod impact testing is a standard method of assessing the impact resistance of materials (Fig. S14, left). A pivoting arm is raised to a specific height (constant potential energy) and then released. The arm swings down hitting a notched sample, damaging the subject (in this case the tag housing, Fig. S14, right). The energy absorbed by the sample is calculated from the height the arm swings to after hitting the sample.

Izod tests were used in this study to assess the robustness of tag designs to lateral forces (e.g., the assumption that potential failure of the tag housing would be caused when the tag is touched by body parts of another
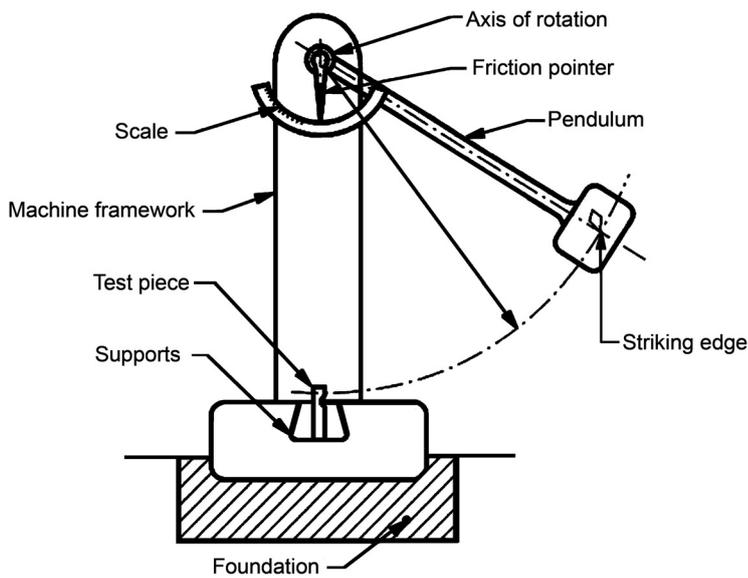
Figure S14: Schematics of an Izod style test (left) and details of the lateral impact experiment used to test the robustness of tag housings (right).

individual or by the tagged whale making contact with the ocean floor). Relative strength of different manufacturing processes was assessed as the force required to damage housings to the extent that tags would no longer be functional. In order to determine the characteristics (e.g., size) of the impact machine, preliminary static tests were performed on an arbor press with a strain gauge pressing on the sample. Results of the Izod style test (Fig. S15) indicated that the tags manufactured with the DMLS procedures are superior in their strength to withstand sideways impact forces. The average force required to damage tags to an extent that they would no longer be function were 200 and 325 Newtons for tags with a welding interface (n = 6 testing tags) and for DMLS tags (n = 7 testing tags), respectively. This difference was statistically significant (Wilcoxon rank test, p = 0.03) and indicates that DMLS tags are more robust.
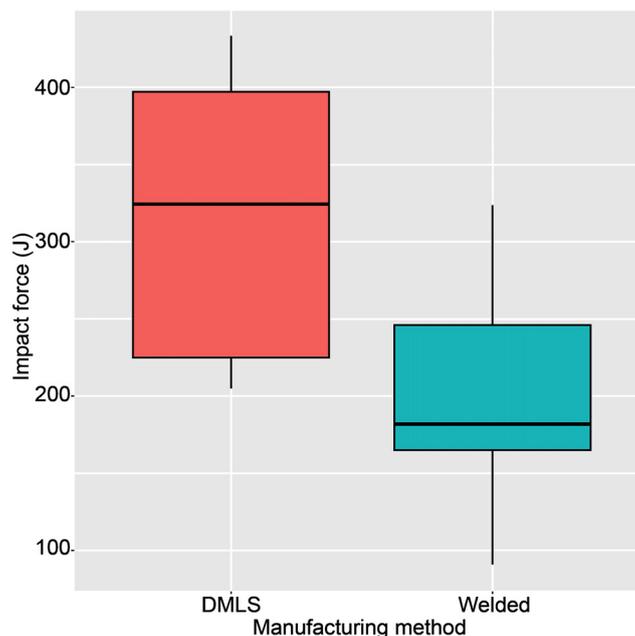

Figure S15: Boxplot comparing of the force (N) required to damage consolidated welded and 3-D printed (DMLS) satellite tags to an extent that they are no longer functional.

SUPPLEMENTARY MATERIAL 3

Damage at the interface between the transmitter and the anchor in a consolidated, interfaced satellite tag
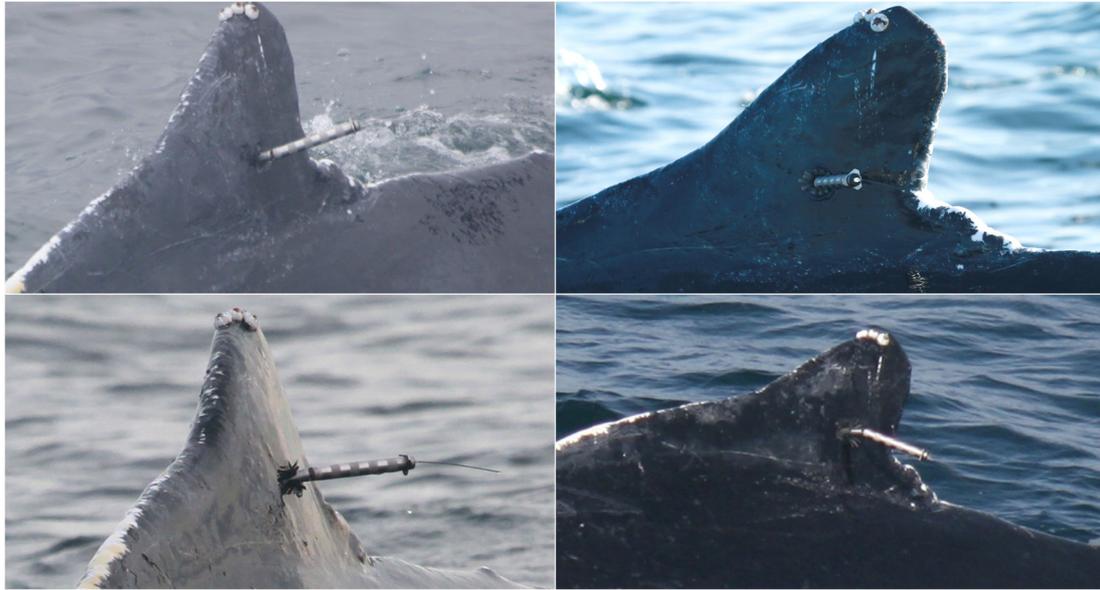

Figure S16: Bending of a consolidated tag at the anchor-transmitter interface one day (top left), three days (top right), four days (bottom left) and five days (bottom right) after deployment. Transmissions ceased on Day 10 after deployment and on the next resighting, 18 days after deployment, the tag had been shed.

SUPPLEMENTARY MATERIAL 4

Damage of the posterior end (epoxy bulb) of a consolidated satellite tag deployed with a pole

Figure S17: Breakage of the epoxy bulb on pole-deployed implantable satellite tags. The broken bulb is shown on the left panel and the broken tag, attached to the whale's body, on the right (credit: Ygor Geyer).

SUPPLEMENTARY MATERIAL 5

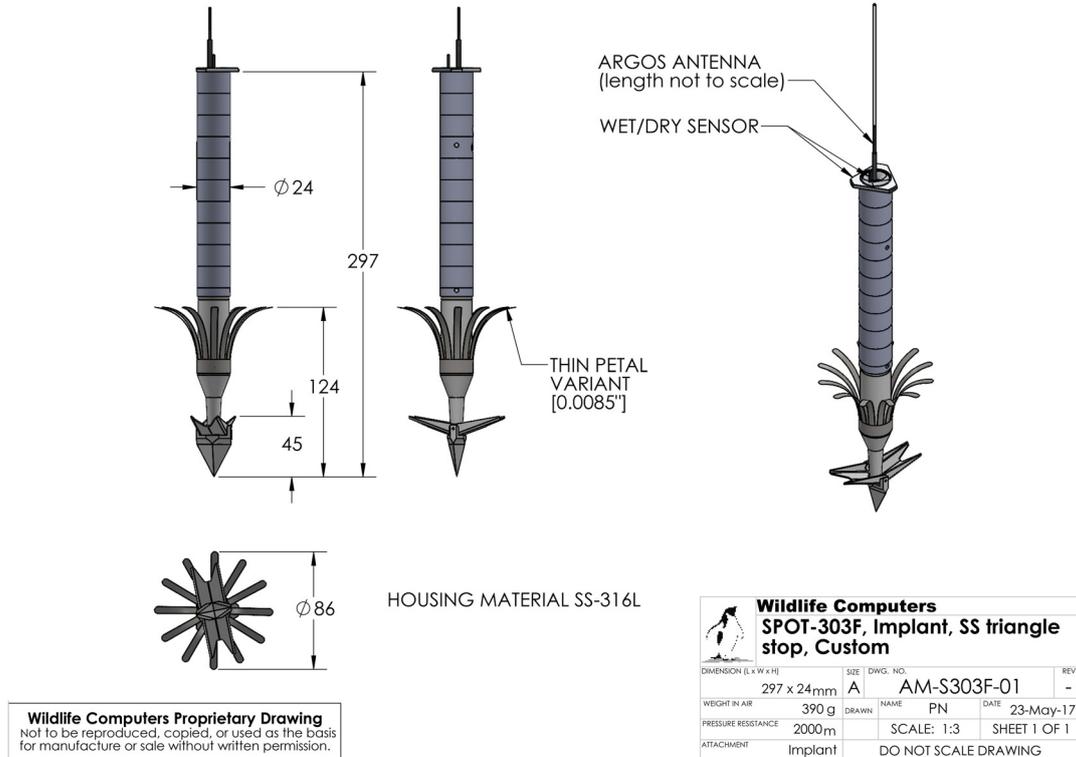## Consolidated large-cetacean satellite tag SPOT-303

Figure S18: Schematic drawing of consolidate tag SPOT-303.

SUPPLEMENTARY MATERIAL 6
Consolidated large-cetacean satellite tag SPOT-372-DMLS
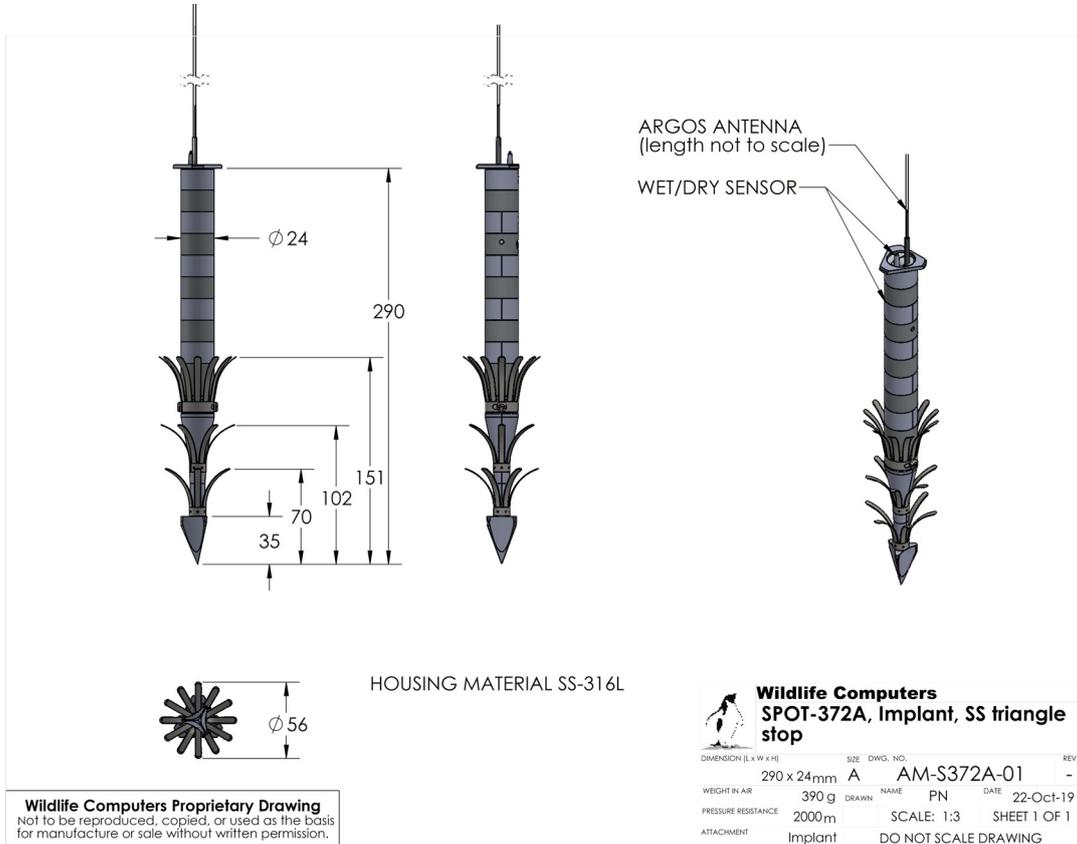

Figure S19: Schematic drawing of consolidated tag SPOT-372.

SUPPLEMENTARY MATERIAL 7
Example of rapid tag egress

Figure S20: An example of abrupt egress exhibited by a SPOT-372 tag. The tag was still well-embedded 13 days after deployment (only 20% exposed) (arrow, top left, photo credit: New England Coastal Wildlife Alliance). The tag egressed to 70% exposure 15 days post-deployment and at 16 days (top right) with no evidence of external forces. Note the extruded blubber plug in the process of being shed (arrow; photo credit: Blue Ocean Society). The transmitter reached 80% exposure 17 days after deployment (note that the blubber plug has been shed; bottom left). The tag stopped transmitting 20 days post-deployment and the transmitter was confirmed to have been shed by day 25 (tag site is shown by the arrow, bottom right).