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Evaluating short- to medium-term effects of implantable satellite tags on southern right whales *Eubalaena australis*

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ABSTRACT: Improving our understanding of the effects of satellite tags on large whales is a critical step in ongoing tag development to minimise potential health effects whilst addressing important research questions that enhance conservation management policy. In 2014, satellite tags were deployed on 9 female southern right whales *Eubalaena australis* accompanied by a calf off Australia. Photo-identification resights (n = 48) of 4 photo-identified individuals were recorded 1 to 2894 d (1–8 yr) post-tagging. Short-term (<22 d) effects observed included localised and regional swelling, depression at the tag site, blubber extrusion, skin loss and pigmentation colour change. Broad swelling observable from lateral but not aerial imagery (~1.2 m diameter or ~9% of body length) and depression at the tag site persisted up to 1446 d post-tagging for 1 individual, indicating a persistent foreign-body response or infection. Two tagged individuals returned 4 yr post-tagging in 2018 with a calf, and the medium-term effects were evaluated by comparing body condition of tagged whales with non-tagged whales. These females calved in a typical 4 yr interval, suggesting no apparent immediate impact of tagging on reproduction for these individuals, but longer-term monitoring is needed. There was no observable difference in the body condition between the 2 tagged and non-tagged females. Ongoing monitoring post-tagging is required to build on the sample size and statistical power. We demonstrate the value of long-term monitoring programmes and a collaborative approach for evaluating effects from satellite-tagging cetaceans to support species management.

KEY WORDS: Satellite tracking · Skin condition · Effects · Cetacean · Health · Body condition · Follow-up-study

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1. INTRODUCTION

Satellite telemetry is an important tool to understand marine mammal behaviour, movement and ecology. Long-term tracking is key in assessing movements and migration, to describe migratory connections and destinations, and to evaluate potential overlap of critical habitats with anthropogenic activities (Mate et al. 1999, 2011, Baumgartner & Mate 2005, Zerbini et al. 2015a). A better understanding of whale movements and residency times facilitates effective conservation and management policies (Andrews et al. 2019).

In general, early satellite tags using the Argos system were relatively large with a sizeable external component, while contemporary tags have been designed to minimise tag size and reduce the external component (Andrews et al. 2019). Andrews et al. (2019) classified cetacean electronic tags into 2 main categories: non-invasive and invasive tags. Non-invasive tags, such as suction cup tags, are those attached to the surface of the body and do not require subdermal anchoring. These tags provide short-term data usually for less than 24 h (Goldbogen et al. 2013, Bejder et al. 2019). Invasive tags were divided into 3 sub-groups: invasive Type A tags are anchored with the electronics package external to the skin, such as LIMPET tags, and when deployed on large whales, they typically provide movement data for a few weeks (Panigada et al. 2017, Owen et al. 2019). Type B tags are bolted to the dorsal fin of small cetaceans and are not commonly used with large whales. Finally, invasive Type C (or 'consolidated') tags correspond to instruments that are partly or fully embedded in the body of an individual and, in large whales, can provide long-term (weeks to months) data (Zerbini et al. 2015a,b, Andrews-Goff et al. 2018, Riekkola et al. 2018, Mackay et al. 2020).

Currently, Type C invasive tags are required to study large-scale migrations because of their relatively long duration (e.g. Zerbini et al. 2015a,b). Satellite tracking using invasive tags has contributed to conservation management of threatened whale populations, including southern right whales (SRWs) *Eubalaena australis* (Best & Mate 2007, Mate et al. 2007, Zerbini et al. 2016, Mackay et al. 2020); North Atlantic right whales *E. glacialis* (Mate et al. 1997); North Pacific right whales *E. japonica* (Wade et al. 2006, Zerbini et al. 2015a); North Atlantic bowhead whales *Balaena mysticetus* (Heide-Jørgensen et al. 2007); humpback whales *Megaptera novaeangliae* (Zerbini et al. 2006, Andrews-Goff et al. 2018, Riekkola et al. 2018, Owen et al. 2019); blue whales *Balaenoptera musculus* (Double et al. 2014, Hucke-Gaete et al. 2018, Möller et al. 2020, Calderan et al. 2023); and gray whales, *Eschrichtius robustus* (Mate et al. 2015).

The performance (e.g. longevity of transmissions) of satellite tags on large cetaceans can vary considerably depending on the tag type, species, reproductive state, geographic location, quality of the attachment and the location on the body where the tag is attached (Slay & Kraus 1998, Best & Mate 2007, Robbins et al. 2013, Best et al. 2015, Norman et al. 2018). For example, transmission duration was lower in SRW females accompanied by a calf than in unaccompanied whales, which was likely due to the relatively high degree of physical contact between a mother and her calf leading to damage to the tag and/or aerial (Best et al. 2015).

There are health concerns associated with the use of invasive satellite tags in large cetaceans, and their potential effects are not well documented or understood for most species (Andrews et al. 2019). Effects from invasive implantable tags can include localised (e.g. extending <30 cm around the tag site) and regional (e.g. extending >30 cm around the tag site) swelling (Weller 2008, Gendron et al. 2015, Norman et al. 2018, Andrews et al. 2019), a small amount of blubber extruding from the tag site, possible muscle injury/trauma, higher-than-normal cyamid (whale lice) infestation and the development of a persistent wound or depression at the tagged site (Weller 2008, Moore et al. 2013, Best et al. 2015). Evaluating such effects can be difficult due to logistical challenges with (1) relocating tagged individuals that are highly migratory, (2) resighting specific tagged individuals within the wider population and (3) accurately assessing and evaluating the physical and physiological effects from a tag (Norman et al. 2018). The invasive nature of Type C implantable tag attachments raises potential concerns over both tissue trauma and infection to the animal, especially for tags that penetrate through the blubber–muscle interface (Weller 2008). Tag development has progressed substantially in recent years, with targeted research identifying areas of improvements in tag design which has led to the development of a sturdier implantable satellite tag design (Robbins et al. 2013). Recent tag designs (Type C) are now fully integrated, meaning that no anchor articulation or tag–anchor interfaces exist (Zerbini et al. 2017). The advanced Type C fully integrated tag has proven more successful than the previous versions that were not fully integrated and were more prone to breakage and technical failure (Zerbini et al. 2015a). In previous tag designs, articulated anchors failed at the articulation point, resulting in premature detachment of the transmitter and part of the anchor being left in the body of the whale. Another weakness was found at the interface between the anchoring system and the electronics, resulting in bending and or breakage of the tag (Robbins et al. 2015). The advanced Type C tags have proven to be more robust and provide greater duration than the previous versions that were not fully integrated and more prone to breakage and technical failure (Zerbini et al. 2015a).

The development of a depression at the tagged site is believed to be the result of muscle damage and shearing where the tag has entered (Mate et al. 2007). Moore et al. (2013) suggested that rigid, implanted devices that penetrate the cetacean blubber–muscle interface could have secondary health impacts. In an assessment of wound healing of tagged gray and blue whales in the eastern North Pacific, Norman et al. (2018) reported that swelling occurred in 74% of re-encountered gray whales tagged with the earlier versions of Type C tag designs, with the highest frequency of swelling occurring 6 mo post-deployment. Depressions occurred in 82% of gray whales and 71% of blue whales (Norman et al. 2018). A long-term evaluation of tag sites on 21 SRWs found that healing at the tag site occurred within 5 yr of tagging (and 2 yr after tag shedding) (Best et al. 2015).

Physiological responses (e.g. swelling of the tag site) in large whales appear to be influenced by the position of the tag, although the ideal tag placement position does vary by species (Norman et al. 2018). Muscle damage is influenced by the position of the tag, muscle movement and body condition. Robbins et al. (2013) described broad swellings at tag sites that were more prevalent when the tag was located on the caudal dorsal side below the horizontal midline (see Fig. 2) of humpback whales than on the cranial dorsal side above the horizontal midline area. Additionally, a decrease in the blubber layer throughout the calving season, particularly for lactating females, could potentially result in deeper penetration of the tag into the muscle layer when tagged on the caudal body (where the blubber layer is also thinner), compared to the cranial dorsal area above the horizontal midline (Best et al. 2015). Based on modelled shearing of blubber relative to muscle on dolphin *Delphinus delphis* cadavers with Type C tags, Moore & Zerbini (2017) hypothesized that depressions and regional swelling (in the short and long term) were likely the result of tissue loss and repair, respectively. Muscle shearing in whales may occur between muscle and blubber during locomotion and can cause a laceration when an implanted tag crosses the blubber–muscle interface due to the shearing action of blubber relative to muscle (Moore et al. 2013). If shearing in dolphins is comparable to large whales, Moore & Zerbini (2017) suggested that placing tags on the cranial half of the body would cause the least trauma.

Despite the range of potential physical and physiological effects to an animal, Type C tags typically seem to have no major impact on the reproductive success or mortality rates of large whales (Best & Mate 2007, Mate et al. 2007, Robbins et al. 2013, Best et al. 2015, Zerbini et al. 2017). Reproductive success was not significantly different for tagged and non-tagged SRWs and humpback whales off South Africa and the Gulf of Maine, USA, respectively (Best & Mate 2007, Best et al. 2015, Robbins et al. 2015). However, Gendron et al. (2015) reported an apparent effect on reproductive success for a satellite-tagged blue whale studied over a 16 yr period (1995–2011). The blue whale's calving history showed a total of 3 calves; 1 in the year prior to tagging (1994), 1 in the year after tagging (1996, when no swelling was observed), and 1 was observed in 2011 after the swelling period (1999–2007). Broad swelling at the tag site was observed 4–12 yr post-tagging, during which period no calf was observed with the female (female was sighted 13 out of 18 years during 1994–2011). Swelling was caused by the reaction to a broken subdermal attachment from a tag designed early in the evolution of large whale tagging that remained embedded for a decade in the whale. It is assumed that the foreign body was expelled from the body based on the reduction of swelling and healing of the open wound site 12 yr post-tagging (Gendron et al. 2015). Tag development has improved substantially in recent years, and it is common practice to use consolidated tag (Type C) designs that prevent breakage to the subdermal attachment (Zerbini et al. 2015a). Gendron et al. (2015) did not discuss body condition. There is a need to understand drivers of changes in reproductive success, including body condition, climate variates and long-term tagging effects. Over the past 20 yr, environmental conditions have been changing, and various species of baleen whales (right, gray and blue whales) have been observed to be in poor body condition (Christiansen et al. 2020, Torres et al. 2022, Wachtendonk et al. 2022, Vermeulen et al. 2023). In some cases, especially gray whales, poor body condition is assumed to increase the calving interval (Torres et al. 2022).

The availability of reports on the effects of satellite tags on cetaceans is limited by the systematic monitoring programmes completing follow-up studies, due to challenges with resighting tagged migratory individuals. Individual sighting histories gained from long-term monitoring programmes are extremely valuable in the assessment of tag effects. Further research is needed to understand short- and medium-term effects of invasive satellite tagging on large whales, especially considering potential intra-specific variation in population parameters and health status (body condition). Andrews et al. (2019) recommended that any tagging programme should include a systematic resighting programme to assess any impacts of that tagging as a core part of the programme.

In the current study, satellite tagging was undertaken between 6 and 8 September 2014 at the major wintering breeding ground for the south-western Australian population of SRWs at the Head of the Great Australian Bight in South Australia. Nine SRWs with calves were tagged (for details on tagging, see Mackay et al. 2020). The research was undertaken to address several priority research questions identified in the Australian Conservation Management Plan for SRWs, specifically to better understand offshore distribution and migration pathways (DSEWPaC 2012, Mackay et al. 2020). The population demographics of the south-western population are well understood, and long-term monitoring has been undertaken through aerial and cliff-based research since the early nineties (Charlton et al. 2022, Smith et al. 2022). The south-western Australian population has an estimated abundance of 2549 individuals (Smith et al. 2022), and the observed mean calving interval is 3.9 yr (95% CI: 3.8, 4.1) (Charlton et al. 2021).

The goals of this opportunistic study were to evaluate short- to medium-term effects of Type C satellite tags on SRWs tagged off Australia. This work is intended to contribute to the understanding of potential effects from invasive satellite tags on whales to inform improved tag design, minimise health effects, promote tag effectiveness and inform conservation management. The specific objectives of this study were as follows: (1) to observe the tag site and assess the effect of tagging on opportunistically resighted SRWs immediately after tagging (1–22 d) and over the medium term (1–8 yr post-tagging) using a consistent health scoring system (Andrews et al. 2019); and (2) to investigate whether satellite tagging affects the body condition of lactating females over time by comparing multi-year measurements of body condition.

2. MATERIALS AND METHODS

Photo-identification (photo-ID) data were obtained for 6 of the 9 tagged whales. Purpose-built satellite-radio Type C implantable tags (320 mm length) were used, consisting of a Spot 5 satellite transmitter encased in a surgical-grade stainless steel housing (Mackay et al. 2015) (Fig. 1). The interface between the anchoring system and the cylindrical electronics housing was reinforced by a stainless-steel collar (Mackay et al. 2020). For more details of tag location on the body (Fig. 2), implantation and transmission success, and Animal Ethics Committee and State and Commonwealth research permits approvals, see Mackay et al. (2015). Satellite tags were deployed from a 5.5 m inflatable vessel. The total number of personnel on the vessel was restricted to 3, preventing a photographer from being onboard. Strict protocols developed by the Australian Antarctic Division, Commonwealth Scientific and Industrial Research Organisation, were employed to avoid undue disturbance during deployments. Tags were deployed using a modified pneumatic line-thrower set at bar 11 of pressure and aimed at the highest point on the cranial dorsal side above the horizontal midline area. For further methodology, see Mackay et al. (2015). SRWs spend extended time beneath the surface, and there are ethical restrictions on approaching individuals. Thus, the tagging process was conducted as accurately as possible while minimising the impacts of tagging. Experienced professionals deployed the tags.

Opportunistic resighting and monitoring of the tagged whales was conducted during the annual cliff-top SRW research programme undertaken at Head of Bight between June and September in 2014–2022. Methods for the collection of sightings

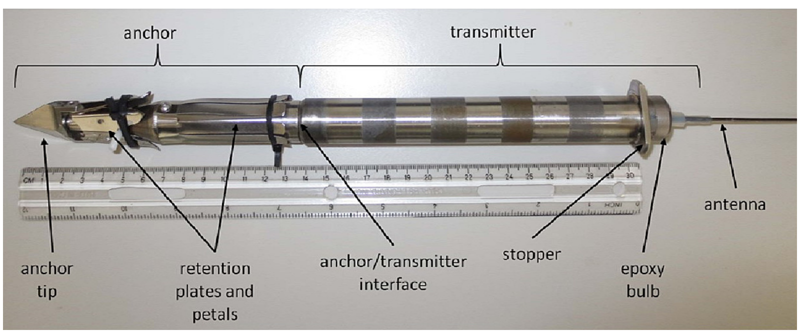

Fig. 1. Example of Type C implantable tag deployed on southern right whales *Eubalaena australis* in South Australia in 2014, showing the spring-loaded anchor, retention plates and petals, anchor–transmitter interface and the antenna (source: Robbins et al. 2013)

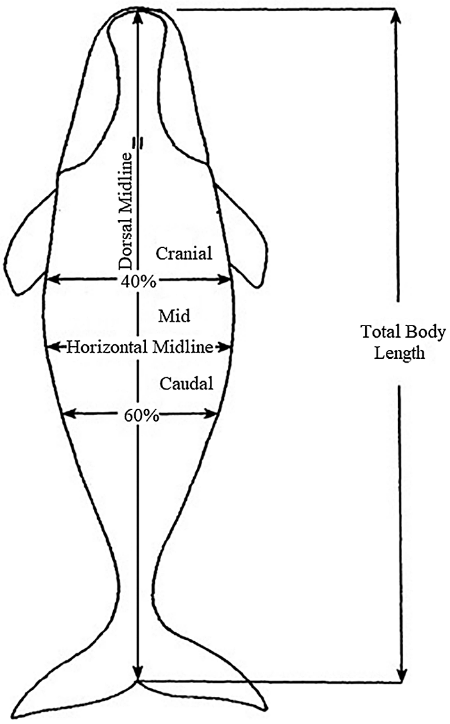

Fig. 2. Southern right whale *E. australis* body morphology and tag location classification. Reference includes left or right of the dorsal midline and cranial or caudal to the horizontal line. The midline represents approximately 50% of the total length of the whale (Miller 2006)

and photo-ID data are described by Charlton et al. (2019). Photographs were obtained from cliff-top survey locations with a Nikon 7100 digital SLR camera with a Sigma 500 mm (effective 750 mm) fixed lens mounted on a Manfrotto tripod. Images of the rostrum from above with left and right lateral perspectives of the dorsal side of the whale were taken for photo-ID resight purposes. Photo-ID images were matched against the Head of Bight photo-ID catalogue (1991–2021, n = 1934 individuals) and the Australasian Right Whale Photo-ID Catalogue (1976–2018), which at the time of matching (March 2020) included 2360 individuals. The tag site was assessed using a health scoring system developed by marine scientists and veterinarians to characterise the tag site features from photographs (Andrews et al. 2019). Each whale was given a total score comprised of the score assigned to each feature, including swelling; skin loss; exudate; tissue extrusion (including none visible, fresh and necrotic tissue); pigmentation change; depression or divot; and cyamids at the tag site, as well as the degree of change across the sighting history (Table 1) (Andrews et al. 2019). A score was given by 2 independent individuals using all images of the tag site available for each day that the whale was sighted, and a monthly average score was calculated. The mean of the 2 observers' scores was taken. The low sample size of whales in this study precluded further statistical analysis or testing of the inter-rater agreement between scores, and observations are presented qualitatively to characterise the observed tag site features.

In 2018, unmanned aerial vehicle (UAV) images were collected, and body condition was measured for 2 females tagged in 2014 and resighted in 2018 with a calf (and non-tagged whales) following methods described by Christiansen et al. (2018). In 2018, 97 female–calf pairs out of 99 were photo-identified using UAV. First, body length and width (at every 5% increment along the body axis) of the whales were measured from aerial images (Christiansen et al. 2016). The body volume of the whales was estimated by modelling the body of the whales as a series of infinitesimal ellipses (for details see Christiansen et

Table 1. Scoring system used to characterise tag site features from photographs (from Andrews et al. 2019)

Feature	Description	Score
Swelling	No visible swelling	0
	Localised, focal, <30 cm diameter	1
	Regional, focal, >30 cm diameter	2
	Irregular size and shape, >30 cm diameter	3
Skin loss	No visible skin loss	0
	Up to 1 cm greater than tag diameter	1
	Up to 3 times tag diameter	2
	Larger than 3 times tag diameter	3
Exudate	No visible exudate	0
	Clear	1
	Blood	2
	Purulent	3
Tissue extrusion	No visible tissue extrusion	0
	Fresh tissue	1
	Necrotic tissue	2
Pigmentation change	Normal pigmentation	0
	Change in colour of skin around tag site	1
Depression / divot	No visible divot	0
	Diameter of tag or less	1
	Up to approximately 3 times tag diameter, shallow	2
	Significantly larger than tag diameter, deep	3
Cyamids at tag site	Absence of cyamids at tag site	0
	Within tag site	1
	Patch extending beyond tag site margins	2

al. 2019). The body condition of the whales was then calculated as the proportional residual of the relationship between body volume and body length, using the best quality measurements from all whales sampled in 2018 (measurements: 409 calves, 43 juveniles, 55 solitary adults, 567 lactating females).

Two modelling approaches were used to assess the potential effects of the tags on (1) the relationship of maternal body condition and calf length and (2) the rate of maternal body condition loss of SRW lactating females.

In modelling approach 1, a generalized linear mixed-effect model (GLMM) was used to compare the body condition (response variable) between tagged and non-tagged lactating females (fixed effect), while accounting for the size of their calf (fixed effect) in the statistical modelling software R 3.6.2 (R Core Team 2019). An interaction term was also included in the model between treatment (tagged vs. non-tagged) and calf length, to determine if the rate of loss in body condition (the slope parameter of the relationship between maternal body condition and calf length) differed between tagged and non-tagged females as their calves grew in length through the 2018 breeding season; a significance level of 0.05 was applied. To account for repeated measurements from the same individual whales, individual ID was included as a random effect in the models. To determine the amount of variance explained by the models, the marginal R^2 (R^2_m, the variance explained by the fixed effects) and conditional R^2 (R^2_c, the variance explained by both the fixed and random effects) were obtained (Nakagawa & Schielzeth 2013) using the 'MuMin' package.

In modelling approach 2, linear models (LMs) were used to assess the rate of loss in body condition over the 2018 breeding season (as a function of day of year) between the tagged and non-tagged females using the statistical modelling software R 3.6.2 (R Core Team 2019). An LM was fitted to each lactating female individually, and a second LM was used to compare the slope parameters (day effect) between the 2 groups (Christiansen et al. 2018). Christiansen et al. (2018) found that a minimum of 4 measurements over at least 20 d was needed to obtain accurate estimates of body condition change in individual whales, and the same threshold was applied when selecting females for the LMs. This resulted in a sample of 1 tagged and 20 non-tagged females.

The diameter of swelling observed on tagged whales was estimated by first using the cliff-based image as a proxy and then comparing this to a UAV image of the same individual and drawing a circle around the proposed swollen area, and then measuring the diameter of the circle on aerial images in 1 cm increments. Swelling was more likely to be observed from cliff-based images, so the measurements using aerial images were an estimation only. The percentage of body length affected by swelling was calculated using 1% increments along the body length and dividing the swelling diameter by the total body length.

3. RESULTS

Photo-ID profiles were available for 6 of the 9 tagged females with a calf. To date, there have been 48 resights of 4 of the identified tagged individuals, at intervals of 1 to 2894 d post-tagging until September 2022 (Table 2). Two of the photo-identified tagged whales were not resighted. A total of 392 (annual mean = 49) cliff-based surveys were undertaken at Head of Bight between 2014 and 2022 (23 June–29 September), 0–8 yr post-tagging event. Cliff-based surveys were conducted weather permitting, with no surveys completed on days with a Beaufort Sea State of 3 or greater, generally between June and September. In the year of tagging (2014), within-season resight data were recorded over a period of 1–22 d post-tagging between 6 and 28 September 2014. The last date of sightings represented the final day of annual field work and not necessarily the departure of the whale from the study site. The return of 2 tagged females (H9319 and H1469) with a calf to the survey area was recorded in 2018, 4 yr (1386–1476 d) post-tagging. In 2022, a third tagged female (H1040) was photographed (not accompanied by a calf) by a citizen scientist on 9 August at Flinders Chase, South Australia (approximately 1000 km from Head of Bight), 2984 d (8 yr) post-tagging. No resights of any tagged whales were reported in 2015, 2016, 2017, 2019, 2020 or 2021.

3.1. Short-term effects (1–22 d post-tagging)

Tag site features, including swelling, skin loss, exudate, tissue extrusion (including nonvisible, fresh and necrotic tissue), pigmentation colour change, depression or divot, and cyamids at the tag site, as well as the degree of change across the sighting history were scored for each whale and presented as a monthly average (Table 3).

Swelling and depressions were the most common effects observed during tag site follow-up. Swelling

Table 2. Photo identification (photo-ID) resight, tag transmission duration, occupancy information (e.g. first to last sighting) and reproductive history data for 4 satellite tagged southern right whale females accompanied by a calf (cow and calf = CC) at Head of Bight (HOB), South Australia, during 2014−2022 (resights were only made in 2018 [n = 2] and 2022 [n = 1]). Photo-ID code corresponds with the HOB long-term photo-ID catalogue codes, the Australasian Right Whale Photo-ID Catalogue (ARWPIC) and tag deployment number (Mackay et al. 2015). NA: not available

HOB Code (ARWPIC): SARDI Deployment no.	Reproductive history by year	Sighting data and occupancy in year of tagging and year of post-tagging resighting				Tag transmission duration (d)
		2014 n sightings (n days post-tagging)	2014 occupancy	Additional sightings: year, n sightings (time post-tagging)	Occupancy	
H1040 (3152): 4	2010 (CC) 2014 (CC)	6 total: all post-tagging (15; 17; 18; 19; 20; 21)	37 d (22/09 to 28/09)	2022, 1 sighting as unaccompanied adult at Flinders Chase, South Australia (8 yr)	NA	2
H9319 (3317): 5	1993 (CC) 2001 (CC) 2004 (CC) 2014 (CC) 2018 (CC)	12 total: 6 post-tagging (1; 9; 10; 13; 18; 19)	42 d (16/08 to 26/09)	2018, 10 total, first sighted pregnant (4 yr)	2018: 90 d (26/06 to 23/09)	5
H1469 (3337): 8	2011 (CC) 2014 (CC) 2018 (CC)	11 total: first sighted pregnant, 4 post-tagging (0; 19; 20; 22)	64 d (25/06 to 28/09)	2018, 17 total (4 yr)	2018: 59 d (23/06 to 20/08)	50
H1436 (3306): 9	NA	5 total: all post-tagging (12; 13; 19; 20; 21)	10 d (19/09 to 28/09)	0	NA	13

was present in 75% (n = 3) of the whales, of which 2 individuals displayed regional swelling (~100 cm; whales H1040 and H1436) and 1 displayed localised swelling (estimated <30 cm; H1469) in the 3 wk post-tagging. Regional swelling at the tag site of H1040 and H1436 was observed 15 and 12 d after tagging, respectively, with no resights of these whales made prior to this time. Changes to the observed swelling were not evident in the short term.

For whales with regional swelling observed in 2014 (H1040 and H1436), the tags were implanted on the dorsal side nearing the mid- to lower caudal area (Fig. 3). Depressions were present for 50% (n = 2) of tagged whales. Effects observed post-tagging also included blubber extruding and skin loss around the tagging site (H1469 and H9319) (Figs. 3 & 4), and pigmentation change (H1469). The tag was partially inserted on deployment in H9319 (Fig. 3A). Observations showed tag expelling with stainless steel protruding from the tag site and water flowing off what appeared to be a remnant of the embedded tag (Day 10 post-tagging, Fig. 4A1), which was not evident 19 d post-tagging (Fig. 4A2). However, the low-resolution of the available images prevented conclusive reports on whether the tag remained in the whale or not. Nineteen days after tagging, the tag was no longer visible (and likely shed), and a minor wound and skin loss were observed around the tag entry point. In addition, cyamids were observed around the tag site.

3.2. Medium-term effects (1–8 yr post-tagging)

Two tagged whales, both with a calf, were resighted in 2018 (4 yr after tagging), which is consistent with an observed 4 yr calving cycle. One individual (H9319) was sighted 10 times (9 times using UAV and 1 time from the cliff top) during a 90 d period and was pregnant when first sighted. It appears that the tag in H9319 was not successfully implanted (estimated 50% implanted) and was shed within 19 d of tagging. There was no evidence of scarring or swelling in the 2018 aerial images (Fig. 5). The other tagged individual (H1469) was photographed by the UAV and from the cliff top 17 times (13 times using UAV and 4 times from the cliff top) over 59 d. Regional, persistent swelling on the cranial left-side dorsal midline and a depression around the tag site was observed for H1469. The swelling increased over time, as localised swelling was observed 3 wk post-tagging and broader persistent swelling was observed 4 yr later (Fig. 6). In 2018, the diameter of the swollen area was estimated to be 1.2 m (or ~9% of the total body length of 13.9 m). Swelling and depression were observed from cliff-top images; how-

Table 3. Scoring of tag site features to assess effects from tagging on southern right whales *Eubalaena australis* off South Australia (average scores from 2 scorers, total score is a monthly average). Tag site category scores range from 0 to 3 for all but tissue extrusion (0–2), pigmentation change (0–1) and cyamids at tag site (0–2), with a maximum total score of 17. Higher scores indicate greater impact to the animal. The method for characterising tag site features to assess effects from tagging on whales is extracted from Gulland et al. (unpubl.) in Andrews et al. (2019). HOB: Head of Bight, South Australia; UAV: unmanned aerial vehicle; NA: not available

Tag deployment No.: HOB code	Month (n days scored)	Days since tagging	Swelling	Skin loss	Exudate	Tissue extrusion	Pigmentation change	Depression	Cyamids	Total score (monthly average)	Tag visible	Comment
4: H1040	Sept 2014 (4)	15–21	1.75	0.3	0	0	0.25	0	0	2.25	Y	Small blubber plug from tag site evident, skin sloughing directly around tag site. Swelling evident
5: H9319	Sept 2014 (4)	1–19	0	1.3	0.5	0.5	0	0	1	2.87	Y	Tag implantation failed with tag >50% out. Superficial cut in skin and some tissue skin loss around tag site. By Day 19 post-tagging, tag expelled and no tissue extrusion.
	Aug 2018 (1)	1442	0	0	0	0	0	0	0	0	N	UAV images; no evidence of tag or scarring
	Sept 2018 (1)	1476	0	0	0	0	0	0	0	0	N	UAV images; no evidence of tag or scarring
8: H1469	Sept 2014 (4)	0–21	0.25	1	0	1.25	0.5	0.25	0	3.25	Y	Minor swelling, skin sloughing around tag site, small depression
	Jun 2018 (1)	1384	0	0	0	0	1	0	0	NA	N	NA score as UAV images do not provide comparative angles
	Aug 2018 (1)	1439	2	0	0	0	1	1	0	4	Y	Condition of tag site was similar or worse than in 2014. Skin loss, tissue extrusion and a depression at tag site. Pigmentation changes improved and swelling increased.
9: H1436	Sept 2014 (3)	12–21	2	2	0	0	0	1	0	5	Y	Swelling evident, skin loss and depression at tag site

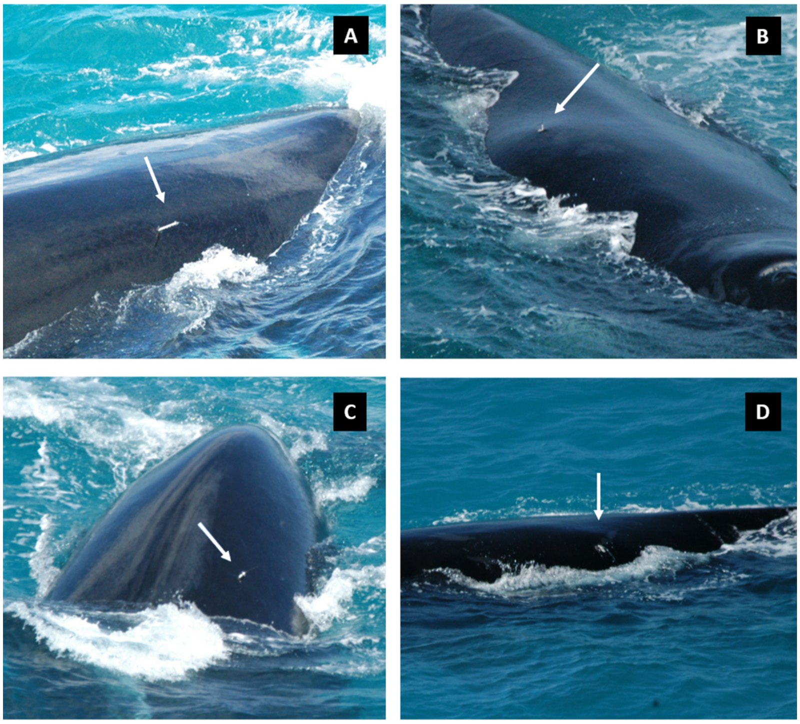

Fig. 3. Images of satellite tag locations on southern right whales *E. australis* tagged at the Head of Bight, South Australia, in 2014. White arrows indicate tag sites. Satellite tag in (A) whale H9319 photographed on the day of tagging, showing partial tag implantation on the right of dorsal midline in the cranial portion of body; (B) H1040 photographed 15 d post-tagging on the dorsal side horizontal midline; (C) H1469 photographed on the day of tagging on the cranial left side of the dorsal midline; and (D) H1436 photographed 20 d post-tagging on the caudal left side of the dorsal midline

ever, the swelling depression was not evident in the aerial photographs taken within 6 d of the cliff-top images (Fig. 6).

The cliff vs. aerial photos provided different perspectives of the whale. From the cliffs, there was obvious regional swelling around the tag site of H1469 (Fig. 6B–E), while from the aerial images the swelling was not visible (Fig. 6A). This information should be considered for development of future follow-up monitoring studies to assess tag effects. When using UAVs to evaluate tag effects, one could underestimate the effect from tagging, but UAV photogrammetry is suitable for quantifying the body condition of whales. It is therefore recommended that tag effects are evaluated using aerial images to assess body condition and lateral images (e.g. cliff-based images, or collected from angles at low altitude via drone) to detect the presence of physiological effects from tagging, i.e. swelling and depressions.

Tagged female H1040 was photographed by a citizen scientist from land on 9 August 2022 accompanied by another adult (not accompanied by a calf) at Flinders Chase, South Australia (ca. 1000 km from Head of Bight) 2984 d (8 yr) post-tagging. In the images (Fig. 7), no prevalent swelling can be observed; however, dermal pallor (pigmentation change) surrounding the tag site is suggested in some of the limited images available. No body condition analysis has been conducted on H1040 from 2022 due to image quality, and no UAV images have been produced. Image quality was insufficient for assigning qualitative health scores.

3.3. Body condition

For modelling approach 1, the GLMM found no difference in the overall body condition between the 2 tagged (10 measurements in total, 8 from H1469 and 2 from H9319, red points in Fig. 8A) and 78 non-tagged females (313 measurements in total, black points in Fig. 8A) (GLMM: $F_{1,78}$ = 0.004, p = 0.948) 4 yr post-tagging. There was also no difference in the rate of loss in body condition as a function of calf length (GLMM: $F_{1,241}$ = 0.909, p = 0.341) (Table 4). All females decreased significantly in body condition as their calf grew in length throughout the nursing season (GLMM: $F_{1,241}$ = 184.4, p < 0.001), at an average rate of −6.7 % (SE = 0.50) per metre increase in calf length (black line in Fig. 8A) (Table 4). The fixed effects (calf length, previous satellite tagging and interaction term) explained 23.6 % (R^2_m) of the variance in body condition, whereas the fixed and random effects (individual variation) together explained 84.9 % (R^2_c) of the variance.

In modelling approach 2, only 1 of the resighted tagged females (H1469, red line in Fig. 8B) and 23 of the non-tagged females (black lines in Fig. 8B) had enough measurements (≥4) over a sufficient period of time (≥20 d) to reliably estimate their rate of loss in body condition as a function of calf length. Female H1469 had a rate of loss in body condition of −3.9 % per 10 d, which was not statistically different (LM: $F_{1,22}$ = 1.258, p = 0.274) from that of non-tagged females (n = 23), which had a mean rate of loss of −2.9 % (SD = 1.0, min = −1.0, max = −5.1) per 10 d (black lines in Fig. 8).

4. DISCUSSION

This paper presents opportunistic observations made on short- to medium-term effects of Type C implantable satellite tags on SRWs off the Head of Bight, South Australia. Of the 9 whales tagged, photo-ID images were obtained for 6 individuals, of which 4 were resighted on subsequent days during the year of tagging (2014), 2 of those females were resighted 4 yr later (2018), and 1 was resighted 8 yr later (2022). Three tagged whales were never photo-identified (or at least the tag site was not observed). The mean resighting rate for all reproductive females at Head of Bight between 1991 and 2016 was 50%, although there was considerable variability in individual resight rates (Burnell 2001, Charlton 2017). Of the 2 tagged whales resighted in 2018, whale H9319 had not been recorded in the survey area for 10 yr prior to tagging in 2014, while the other tagged whale (H1469) had been recorded in the study area 3 yr prior to tagging. One individual (H1436) was recorded in the survey area for the first time in the year it was tagged and was only resighted again that same season and not since. The lack of resights of tagged females in the survey area in the years since tagging could be attributed to a missed sighting event (i.e. the animal may have been in the area and not captured by photo-ID), individuals being present in the calving ground but outside the area covered by the sampling effort or individuals having moved between calving grounds as previously recorded through photo-ID and biopsy data (Pirzl et al. 2009). In 2022, H1040 was

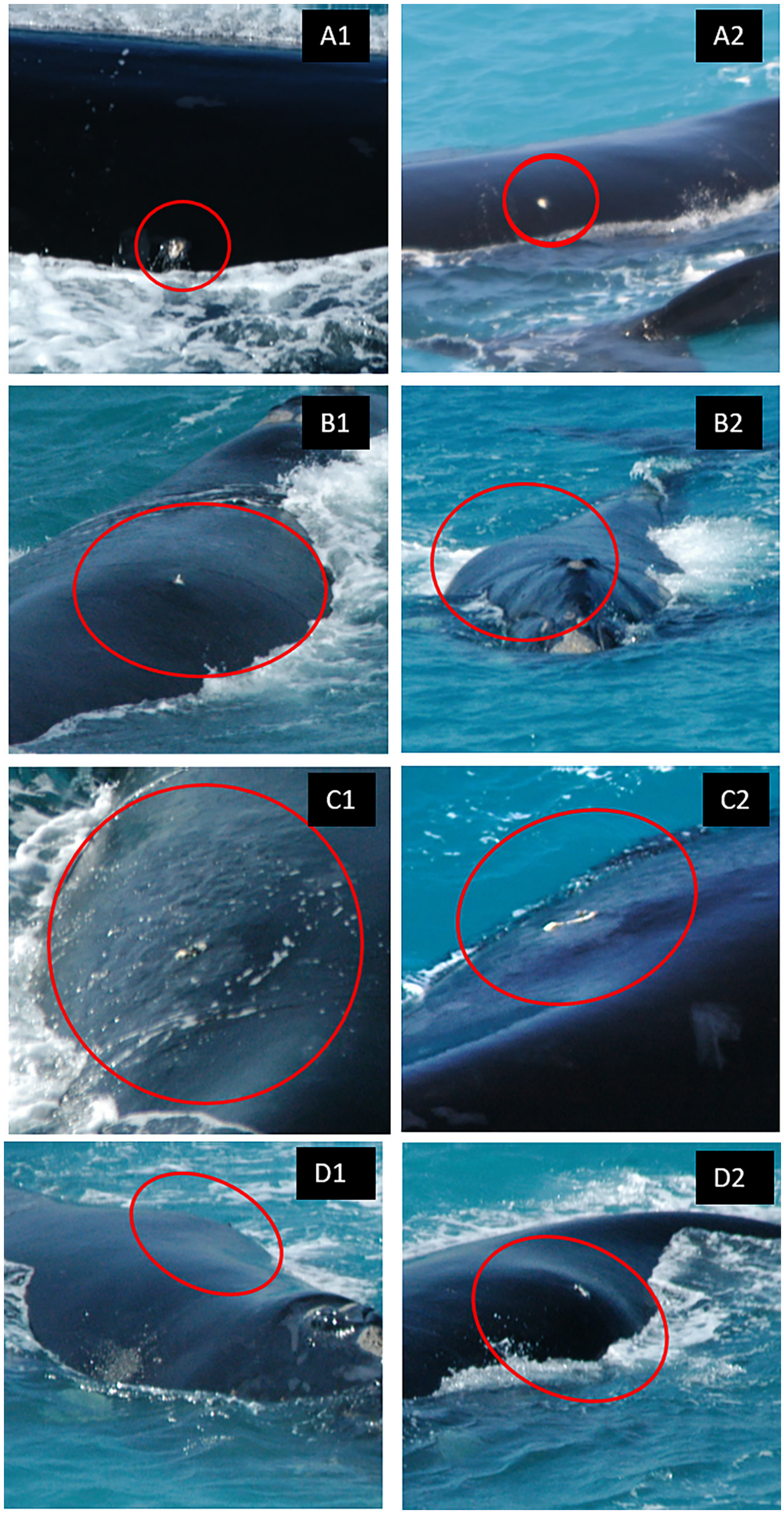

Fig. 4. Images of satellite tag sites on southern right whales *E. australis* tagged in South Australia in 2014. (A) H9319 with stainless steel protruding from the tag site and water flowing off what appears to be a remnant of the embedded tag (A1: Day 10 post-tagging) and expelled tag (A2: Day 19 post-tagging). (B) H1040, showing regional swelling around the tag site (B1: Day 15 post-tagging; B2: Day 18 post-tagging). (C) H1469 with blubber extruding from a wound around the tag site (C1: Day 19 after tagging; C2: Day 21 after tagging). (D) H1436 with regional swelling around the tag site (D1: Day 13 post-tagging; D2: Day 19 post-tagging). Red circle indicates tagged area

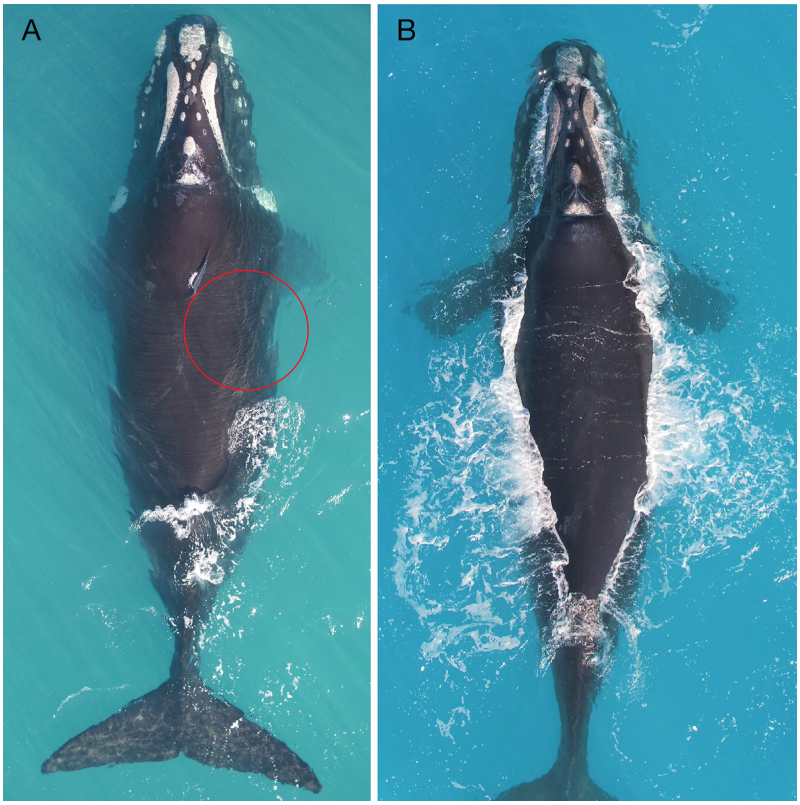

Fig. 5. Aerial images of a satellite-tagged female southern right whale *E. australis* (individual code H9319) in South Australia in 2018, showing no scarring or swelling 4 yr after tagging: (A) pregnant on 26 June 2018; (B) with calf (out of frame) on 4 September 2018. Approximate tag location is indicated by the red circle

observed off Flinders Chase, South Australia. Due to limited reduced quality land-based photographs, a quantitative body condition assessment or qualitative health score was not possible. The Australasian Right Whale Photo Identification Catalogue is not fully reconciled post 2012, so it is possible that the tagged individuals have been sighted but data are not yet available. It is also possible that the animals visited the Australian coastline and were not observed or photo-identified by researchers. It is not possible to rule out that individuals were not resighted because of mortality. However, previous studies have not shown a difference in mortality rates between tagged and non-tagged whales (Robbins et al. 2013).

The observed effects of satellite tagging on SRWs are comparable to those documented for other whale species (Robbins et al. 2013, Norman et al. 2018). Swelling and depressions were the most common effects observed for the resighted tagged whales, which is consistent with results reported for tagged gray and blue whales (Norman et al. 2018). These authors indicated evident swelling on 74% of gray whales using older tag designs, and this percentage reduced with tag improvements. Similarly, swelling was evident for 75% (n = 3) SRWs resighted in our study. The characterisation of regional swelling on SRWs is comparable to a high-grade swelling as defined by Norman et al. (2018): a broad area affected or width/length greater than the height of the dorsal ridge. In this study, one high-grade regional swelling measuring 1.2 m in diameter (8.9% of total body length) was observed 4 yr after tagging (H1469, Table 3). It is plausible that swelling occurred due to the presence of a foreign body (a broken tag part), that the tag site was infected, or a combination of both. Measurement of swelling diameter was attainable for only the 2018 resights due to the introduction of UAV and photogrammetry assessments at Head of Bight in 2016. Localised swelling was observed in only 10% of cases assessed using aerial photography for SRW tagged off South Africa (Best & Mate 2007). The findings of our study showed that the broad swelling observed from lateral images was not detectable by high-quality UAV aerial images (Fig. 6). Aerial photography is commonly used in great whale studies for population assessments. Whilst aerial photography is an excellent tool for photo identification and body condition studies, to assess other health indices such as swelling and skin conditions, including divots and lesions, lateral perspectives can provide greater detail required for assessment. Therefore, it is possible that Best & Mate (2007) underestimated the occurrence of swelling due to the inability to detect swelling from the aerial observation platform used for monitoring.

Depressions were observed in 82 and 71% of gray whales and blue whales, respectively (Norman et al. 2018), and we reported depressions in 2/4 (50%) cases. The depressions observed for the SRWs in this study are comparable to those described by Norman et al. (2018) as a low-grade depression (H1469) and medium-grade severity (localised area and/or less than height of dorsal ridge/fin) (H1436). The pigmentation changes observed in this study (H1040, H1469) were also comparable to the low-grade discolouration composed of a small, localised area and lighter

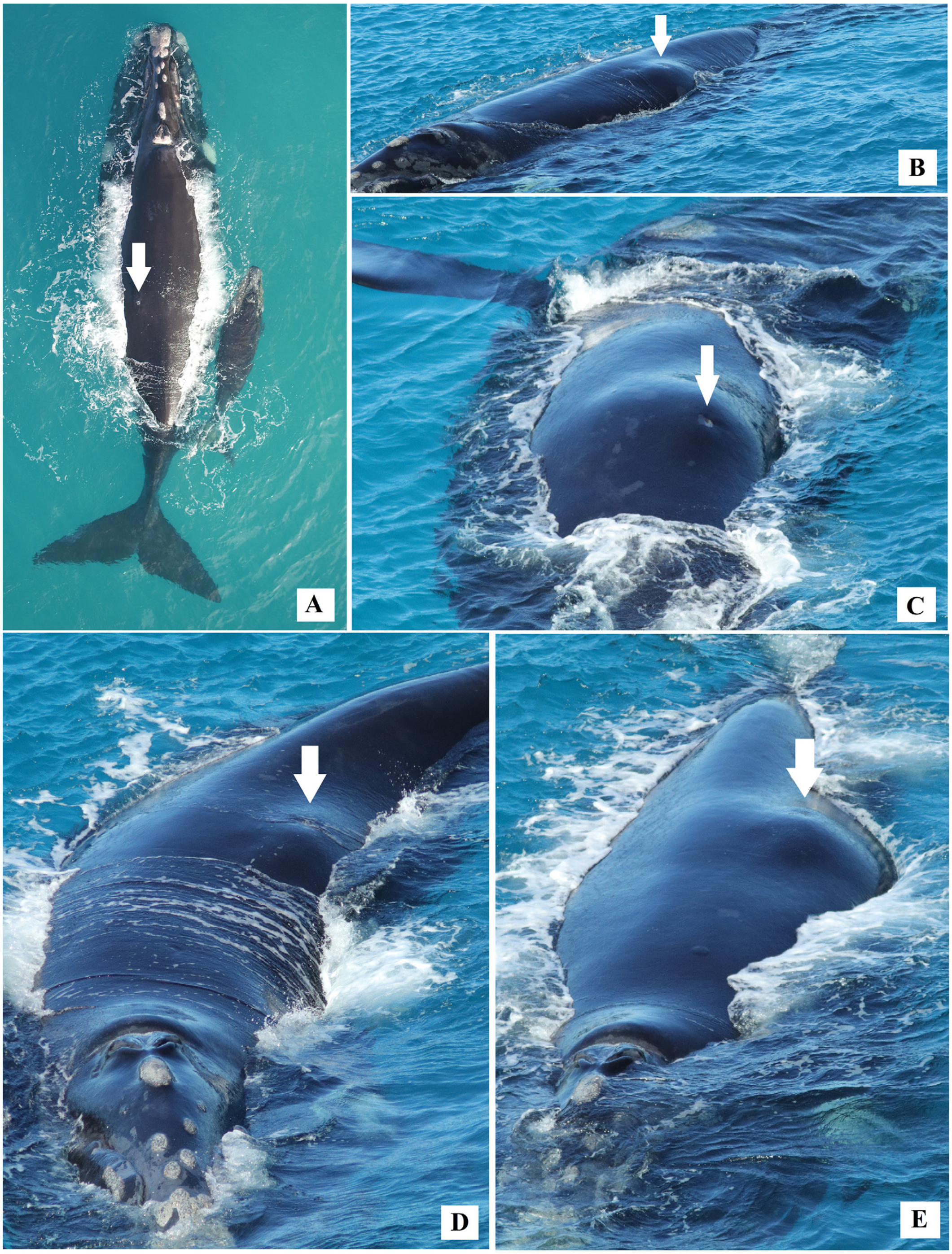

Fig. 6. Images of a satellite-tagged female southern right whale *E. australis* (individual code H1469) in South Australia in 2018, showing persistent swelling at the tag site 4 yr after tagging. White arrow shows the tag location in each photo. (A) Aerial image, 23 August 2018. (B) Left side lateral, 17 August 2018. (C) Cropped tag site, 17 August 2018. (D) Front on curved body, 17 August 2018. (E) Front on straight body, 17 August 2018

grey as described by Norman et al. (2018). Robbins et al. (2013) described the effects of implantable tagging on humpback whales, reporting broad swellings that persisted over extended periods (at least 391 d in 1 animal) and appeared to be related to tag breakage or body location. Best & Mate (2007) reported only 1 case of localised swelling in 10 tagged SRWs, but also described divots and scars often associated with cyamid accumulation as a common feature of tag wound sites.

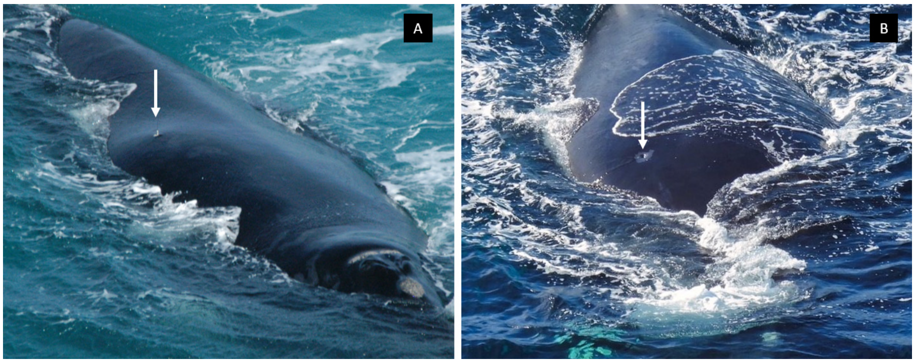

Fig. 7. Images of a satellite-tagged female southern right whale *E. australis* (individual code H1040) (A) in 2014, when tagging took place at Head of Bight, and (B) in 2022, when H1040 was sighted in Flinders Chase, South Australia, 8 yr after tagging. White arrow indicates tag location

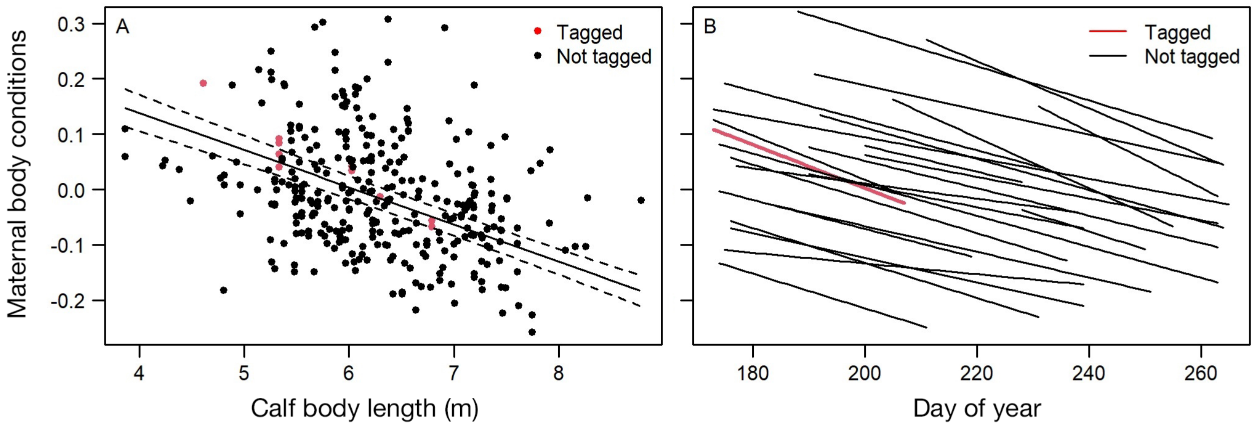

Fig. 8. (A) Female southern right whale *E. australis* body condition (BC) measurements (as a function of calf body length [CL] and previous satellite [SAT] tagging: BC ~ CL × SAT) from previously tagged (red points; n = 10 measurements from 2 females) and non-tagged (black points; n = 313 measurements from 78 females) lactating females, as a function of calf body length. The solid black line represents the fitted values of the generalized linear mixed-effect model (modelling approach 1), and the dashed lines represent 95% confidence intervals. (B) Intra-seasonal changes in body condition of previously tagged (red line; n = 1 female) and non-tagged (black lines; n = 23 females) southern right whales. Each solid line represents the fitted values of a linear model fitted to each whale

Persistent swelling appears to be related to tag breakage and/or body location (Robbins et al. 2015). For example, swelling was common in blue whales with early tag designs but are becoming rarer with current models, possibly because design flaws were corrected (Mate et al. 2007). Andrews et al. (2019) provided detail on tag improvements made and recent developments in tag design. It is now common practice to use fully integrated tags that do not have weak points at the articulate anchor or interface between tag and electronics (Zerbini et al. 2015a). Mitigating breakage reduces the risk of foreign body response to embedded tag remnants and prevents persistent swelling and promotes wound healing. Tag location, administration of antiseptics and sterilisation practices are also improvements to tagging studies suggested by Andrews et al. (2019).

Successful calving events at a 'normal' mean interval of 4.5 ± 2.1 yr were reported post-tagging for 6 out of 7 tagged females off South Africa (Best & Mate 2007). Similarly in this study, 2 tagged females (H9319 and H1469) returned to calve 4 yr after tag-

Table 4. Generalized linear mixed-effect model of southern right whale maternal body condition (BC) as a function of calf body length (CL) and previous satellite (SAT) tagging: BC ~ CL × SAT. Individual ID was included as a random effect. N = 323 measurements from 80 females

Parameter	Value	SE	df	*t*	p
Intercept	0.403	0.0353	241	11.40	<0.001
CL	−0.067	0.0050	241	−13.30	<0.001
SAT	0.214	0.2380	78	0.90	0.371
CL × SAT	−0.033	0.0349	241	−0.95	0.341

ging. The mean observed calving interval for SRWs in Australia was 3.9 yr (Charlton et al. 2021), and the tagged females were recorded on a 4 yr calving interval. Therefore, there appears to be no effect on reproduction for these individuals, in the cycle proceeding the tagging event. Although the sample size and statistical power are very low, these findings present valuable knowledge to further our understanding of the effects of tagging on great whales.

Monitoring of tagged females over decades and larger sample sizes are required to better understand long-term tag effects on reproductive success, calf survival and body condition, as well as the effects of the locality of the tag on the body, success of the tag implantation and water quality parameters during tag deployment. While satellite tagging of 2 of the 3 resighted SRWs in this study did not appear to have an effect on female calving rates from the limited sample size and duration, ongoing monitoring should be undertaken to assess the possibility of long-term effects on reproduction and health. There is a need to collect resight data of tagged whales at various intervals post-tagging (i.e. 1 or more years), not just the 8 yr post-tagging presented in this study. It is important to understand drivers of changes to reproductive cycles, including body condition and climate variables, to be able to assess long-term tagging effects. As climate change becomes an influential factor in the functionality and efficiency of our oceans, the decline in availability of crucial prey can lead to reduced body condition within a year (Braithwaite et al. 2015). The impacts on ecosystems are non-uniform across space and time, and therefore create more variability within populations and individuals (Lenoir et al. 2020).

In summary, the observed short- to medium-term effects of satellite tagging on SRWs included persistent regional swelling, small depressions at the tag site and some changes in the pigmentation colour. The 2 tagged SRWs resighted in subsequent years (4 yr post-tagging) in the survey area (with sufficient data for body condition and health assessments) showed no noticeable impact to their body condition or observed calving interval. Data are not yet available to determine if calf growth or survival was affected due to energetic consequences of the mother. Indirect health implications from tag-associated lesions could not be assessed in this study. However, long-term monitoring of SRWs in Australian waters aims to provide data to assess the long-term health of tagged individuals.

This study highlights the value of multi-institutional collaboration and the need for ongoing follow-up studies. This work is intended to contribute to our understanding of potential health effects on whales from invasive tags, to help inform improved tag design, to promote tag retention and transmission effectiveness and to improve animal welfare. Greater understanding of the effects of implantable satellite tags on large whales is a critical step towards continued tag development to address important research questions needed to enhance conservation and management policies.

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