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Original Article

Attaching Transmitters to Waterbirds Using One Versus Two Subcutaneous Anchors: Retention and Survival Trade-Offs

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ABSTRACT A major challenge of wildlife telemetry is choosing an attachment technique that maximizes transmitter retention while minimizing negative side effects. For waterbirds, attachment of transmitters with subcutaneous anchors has been an effective and well-established technique, having been used on >40 species. This method was recently modified to include a second subcutaneous anchor, presumably increasing transmitter retention beyond that of single-anchor attachments. This putative benefit may be offset, however, by increased health risks related to additional incisions and subcutaneous protrusions. To test this potential trade-off, we attached radiotransmitters to molting and wintering surf (*Melanitta perspicillata*) and white-winged scoters (*M. fusca*) during 2008 and 2009 in Washington State and southeast Alaska, USA, using single- (121 scoters) and double-anchor (128 scoters) attachment techniques. We estimated daily probabilities of survival and radio retention for each group, this being apparent retention for wintering scoters because we could not differentiate shed transmitters from flighted emigration. For scoters during the flightless remigial molt, we found that addition of a second anchor increased cumulative retention probability ($\pm$SE) over a 49-day period from 0.69 ± 0.11 for single-anchor to 0.88 ± 0.07 for double-anchor attachments, while having no effect on survival. However, during winter, scoters with double-anchor attachments experienced no improvement in apparent retention, while having significantly lower survival during their first 14 days following transmitter attachment; of 15 mortalities during this period, 11 had 2 subcutaneous anchors. From day 15 onward, winter survival rates were nearly identical for single- versus double-anchor attachments, indicating that adverse effects of subcutaneous anchors were mainly limited to the 14-day postattachment period. Overall, given that the survival cost of adding a second subcutaneous anchor was substantial for wintering scoters—decreasing 14-day survival by 12% for adults and 23% for juveniles—we recommend that researchers opt for single-anchor attachments under most circumstances, especially during winter when birds may be energetically challenged. Published 2017. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS Alaska, subcutaneous anchor, surf scoter, survival, telemetry, transmitter attachment, transmitter retention, waterbirds, white-winged scoter.

Radio and satellite telemetry have revolutionized wildlife research by providing valuable information about animal movements and population demography that is difficult or impossible to collect by other means (Millspaugh and Marzluff 2001). Advances in technology have miniaturized transmitters and increased battery life, making telemetry suitable for a wide range of species and research projects (Barron et al. 2010). Despite these advances, attachment of transmitters to free-roaming animals remains a common challenge, particularly regarding transmitter retention and animal welfare. Nonetheless, this challenge is rarely

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addressed with designed research, creating a need for studies that rigorously evaluate the pros and cons of various transmitter attachment methods (White et al. 2013).

The choice of transmitter attachment technique depends on numerous factors, including ecology of the study species, duration of the study, transmitter size, handling time, and potential for adverse side-effects. For aquatic birds, several studies have recommended surgical implantation of transmitters into the coelemic cavity, noting that implanted devices maximize retention without consistent detrimental effects on behavior and health (Iverson et al. 2006, White et al. 2013; but see Latty et al. 2010). However, surgically implanted transmitters are not a viable option for many studies; opening the coelemic cavity requires antiseptic conditions, specialized veterinary surgeons, and general anesthesia, all of which increase the costs and logistical complexities of transmitter attachment. Further, implanted transmitters are intended to remain for the life of the bird, which is often years beyond the battery life of the transmitter. Instead, many researchers opt for external attachment of transmitters to aquatic birds, prioritizing their benefits of easier attachment, short handling times, and affordability over potential drawbacks of short retention times and hydrodynamic drag (Iverson et al. 2006). Transmitters have been externally attached to aquatic birds using a variety of techniques, including harnesses, collars, glue, subcutaneous anchors, and tail mounts. Of these, subcutaneous anchor attachment (hereafter, anchor) has proven popular for aquatic birds because of its favorable retention times and ease of attachment in the field, having been used on >40 species. This technique uses a transmitter with a small anchor-shaped stainless steel wire that projects from the anterior end. The anchor is inserted into a small incision in the middorsal region of the bird, subcutaneously securing an otherwise external transmitter unit.

Originally developed in the early 1990s (Mauser and Jarvis 1991, Pietz et al. 1995), the anchor attachment technique was modified in 2008 to include a second anchor that secures the posterior end of the transmitter (Lewis and Flint 2008). Since that time, the double-anchor attachment technique has been widely used with the intent of increasing transmitter retention beyond that of a single-anchor attachment (e.g., Lewis et al. 2010, 2011; Dickson et al. 2012; Uher-Koch et al. 2014, 2016; Enstipp et al. 2015). The putative benefits of additional retention time may be offset, however, by an increased risk to avian health. This is because the double-anchor technique requires a second incision and subcutaneous anchor, which may increase the risk of bacterial infections, discomfort, behavioral changes, and mortality (Enstipp et al. 2015). However, these potential trade-offs have never been formally tested, providing uncertainty as to the benefits and drawbacks of single- versus double-anchor attachment of transmitters.

We attached otherwise identical transmitters to scoters using either the single- or double-anchor technique, thus creating 2 groups of marked individuals that differed only in the type of attachment technique used. Specifically, we used single- and double-anchor attachment methods to equip surf scoters (*Melanitta perspicillata*) and white-winged scoters (*M. fusca*) with radiotransmitters during remigial molt and winter, providing a direct contrast of the single- and double-anchor techniques for transmitter attachment. We used 2 criteria to compare attachment techniques: 1) probability of transmitter retention over time and 2) survival rate of marked birds.

STUDY AREA

Our study occurred in temperate coastal habitats of the north Pacific coast, including the Salish Sea in Washington State and Seymour Canal and Stephens Passage in southeastern Alaska, USA. Our Salish Sea study area, which included sites in Padilla Bay (48.6°N, 122.6°W) and Forbes Point (48.4°N, 122.7°W), was characterized by intertidal mudflats, seagrass beds, and shallow waters; while Seymour Canal (58.1°N, 134.4°W) and Stephens Passage (58.4°N, 134.5°W) contained diverse shoreline types, including rocky and soft-bottom intertidal habitats, alongside deep channels and fjords. We studied scoters in the Salish Sea and Seymour Canal during their remigial molt; >20,000 scoters molt in the Salish Sea, constituting their main molting grounds south of Alaska, while ≥16,000 scoters undergo remigial molt in Seymour Canal (Uher-Koch et al. 2014). At Stephens Passage, we studied scoters during the winter season, where >10,000 scoters overwinter from late November through March (Uher-Koch et al. 2016).

METHODS

Capture and Radiotracking

We captured surf and white-winged scoters during 2 phases of their annual cycles: 1) flightless remigial molt, from late July through mid-September of 2008 and 2009, in the Salish Sea of Washington State and Seymour Canal of southeastern Alaska (Dickson et al. 2012) and 2) winter, from 17–30 November during 2008 and 2009, in Stephens Passage of southeastern Alaska (Uher-Koch et al. 2016). We used underwater gill nets to capture molting scoters during their escape dives and floating, above-water mist nets to capture wintering scoters in flight (Kaiser et al. 1995, Dickson et al. 2012); otherwise, our handling and processing techniques were identical for molting and wintering scoters. We transported captured birds to shore in small kennels for processing and marked each with a uniquely numbered metal tarsal band. We used plumage characteristics to determine species and sex of each captured bird and measured bursal depth to characterize age class as either immature (hatched previous summer) or adult (hatched ≥2 summers ago; Mather and Esler 1999). We also recorded ninth primary length for molting birds, allowing us to estimate each bird's remaining duration of flightlessness (Dickson et al. 2012).

We attached very-high-frequency radiotransmitters to 92 surf and 47 white-winged scoters during molt, and 110 surf scoters during winter, distributing our sample among sex and age groups (Table 1). Of the 139 transmitters attached to molting scoters, 35 were deployed in Washington State (27 surf scoters, 8 white-winged scoters), and 104 in southeastern Alaska (65 surf scoters, 39 white-winged scoters).

Table 1. Sample sizes, according to species, sex, and age class, for radiotransmitters attached to surf and white-winged scoters using single- and double-anchor attachment techniques during the flightless remigial molt and winter in Washington State and southeastern Alaska, USA, 2008–2009.

	Molt		Winter	
Sample category	**Single-anchor**	**Double-anchor**	**Single-anchor**	**Double-anchor**
Surf scoter				
Male	24	19	25	33
Female	21	28	28	24
Adult	33	36	24	31
Immature	12	11	29	26
Total	45	47	53	57
White-winged scoter				
Male	16	15		
Female	7	9		
Adult	15	13		
Immature	8	11		
Total	23	24	0	0

Transmitters had a mass of 13 g and were 30-mm length × 27-mm width × 15-mm height. Transmitters were equipped with a mortality sensor that doubled the signal pulse rate when animal movement ceased for ≥12 hr. Single- and double-anchor transmitters were identical, with the exception that double-anchor transmitters had a small wire barrel (<0.5 g) attached to the posterior end to accommodate the second subcutaneous anchor (Lewis and Flint 2008). We used subcutaneous anchors to externally mount transmitters in the middorsal region between the scapulae, randomly assigning birds to receive either 1 (121 scoters) or 2 anchors (128 scoters; Table 1). We ensured that the looped end of the anchor wire was firmly closed to prevent potential bill entanglement (Bond and Esler 2008). To insert stainless steel anchors, we lifted the skin away from the musculature and made a 2–3-mm incision in the skin using a sterile No. 11 scalpel blade. We threaded the anchor through the incision 1 prong at a time and immediately sealed the incision with veterinary-grade glue (Vetbond, 3M, St. Paul, MN, USA), adding additional glue to further secure the base of the transmitter to a few dorsal feathers. We sterilized all subcutaneous anchors and the site of incision with isopropyl alcohol or betadine prior to transmitter attachment, and the entire procedure typically required 10–15 min. See Pietz et al. (1995) and Lewis and Flint (2008) for detailed methods regarding single- and double-anchor attachment techniques, respectively. Our research was conducted under United States and Canadian Federal Bird Banding Permits and Animal Care Protocols authorized by Simon Fraser University's Animal Care Committee (Permit No. 868B). We attempted to locate all radiomarked birds every 2–3 days using 4-element Yagi antennas from shore, boats, and occasionally aircraft. When transmitters emitted mortality signals, we confirmed mortalities by locating the transmitter and recovering the carcass, or documenting other probable evidence of death (e.g., transmitter in nest or den of predator, transmitter near feathers or blood). On rare occasions, we found transmitters emitting mortality signals in the intertidal zone with no obvious signs of death; for these birds, we could not differentiate mortality from transmitter shedding, and thus censored these data from our analyses. Data generated during this study are available at https://doi.org/10.5066/F79S1PZJ.

Analyses

Transmitter retention.—We used the nest survival model of Program MARK version 8.0 (http://phidot.org/software/mark/index.html) to quantify retention of radiotransmitters affixed to scoters using single- versus double-anchor attachments. The nest survival model is recommended for ragged telemetry data such as ours, where individuals are monitored at irregular time intervals and the exact date of death may not be known (Dinsmore et al. 2002, Rotella 2006). For our first analysis, we evaluated transmitter retention for surf scoters during winter in southeastern Alaska by means of daily probability that a radio signal was received. Radio signals may be permanently lost under 3 main scenarios: 1) transmitters are shed into the water, upon which their signal becomes attenuated and unavailable for detection; 2) individuals move outside the study area; or 3) transmitters electronically fail. We were unable to distinguish among these fates; therefore, we considered this analysis to be an indicator of transmitter retention and not a direct assessment, assuming there was no systematic bias in movements or radio failure based on number of anchors. However, this uncertainty in radio fate was partially minimized because we deployed our transmitters in late November, at which point autumn migration had ceased and winter site fidelity for surf scoters and other sea ducks is generally high (Iverson and Esler 2006, Kirk et al. 2008). Our encounter histories for this analysis were coded with 4 types of information per individual: 1) the day of transmitter attachment (i), scaled so that $i = 1$ for each individual; 2) the last day the radio signal was received (j); 3) the last day the transmitter was monitored (k); and 4) the radio fate (f), where $0 =$ the radio signal never permanently disappeared and $1 =$ the radio signal permanently disappeared. Detected mortalities were given a fate of 0 (i.e., signal never disappeared) because the transmitter was retained up to the mortality event. We restricted our analysis to a period of 120 days from radio attachment, at which time scoters began to leave our study area for their spring staging grounds (Lok et al. 2012).

We evaluated a candidate set of 16 models to examine variation in daily probability that a radio signal was received. Our model set consisted of a null model with only an intercept, and all additive model combinations of the following covariates: day (days since transmitter deployment [continuous from 1 to 120]), sex (male, female), age (immature, adult), and anchor type (single, double-anchor attachment). Although we had no *a priori* reason to expect that transmitter retention varied by sex or age, we included these covariates in our models to account for sex- and age-specific movement patterns that could influence our ability to detect radio signals. We used an information-theoretic approach to model selection (Burnham and Anderson 2002), in which model parsimony was compared using Akaike's Information Criterion adjusted for small sample sizes (AIC_c) and AIC_c weights (w_i). For each covariate, we summed w_i across all models in which it appeared, producing a parameter likelihood ($\sum w_i$) scaled from 0 (not supported in having explanatory value) to 1 (highly supported). Estimation of $\sum w_i$ was viable for our model set because each covariate appeared in an equal number of models. We based inference of covariates on a combination of 1) model selection metrics (ΔAIC_c, w_i); 2) $\sum w_i$; and 3) magnitude and precision of parameter estimates, basing each covariate's parameter estimate on the best-fitting model in which that covariate occurred. We present parameter estimates as $\beta \pm$ standard error (SE; Burnham and Anderson 2002), whereby the estimate for anchor is the effect of double anchors relative to single anchors, the estimate for age is the effect of immatures relative to adults, and the estimate for sex is the effect of females relative to males.

For our second analysis, we evaluated transmitter retention for molting surf and white-winged scoters in Washington State and southeastern Alaska, again using nest survival models to estimate the daily probability that a radio signal was received. We restricted our data set to the flightless period to increase the likelihood that lost radio signals were caused by transmitter shedding and not emigration from our study areas. Moreover, survival of radiomarked scoters during the flightless molt was nearly 100%, reducing the possibility that transmitters from depredated scoters were lost underwater and misinterpreted as shed transmitters (Uher-Koch et al. 2014). Accordingly, we interpreted our models as daily probabilities of radio retention, rather than signal reception, greatly increasing our scope of inference. For each individual, we limited our data set to dates from capture to recovery of flight, estimating the date at which flight was recovered, F, as

$$F = \frac{N - C}{R} + D$$

where N is the minimum ninth primary length at which scoters can fly (surf scoter: $M = 158$ mm, $F = 139$ mm; white-winged scoter: $M = 179$ mm, $F = 164$ mm); C is the ninth primary length at the time of capture; R is the mean rate of ninth primary growth (surf scoter: 3.9 mm/day; white-winged scoter: 4.3 mm/day); and D is the date of capture (Dickson et al. 2012). Also, we added 3.65 days to F for all scoters captured with ninth primary length $= 0$ to account for a pre-emergence period that occurs after old primaries are shed and before new ones become visible (Dickson et al. 2012). Our encounter histories for each individual were coded as follows: 1) the day of transmitter attachment (i), scaled so that $i = 1$ for each individual; 2) the last day the radio signal was received or the day flight was regained (j); 3) the last day the transmitter was monitored or the day flight was regained (k); and 4) the radio fate (f), where $0 =$ the radio signal never disappeared and $1 =$ the radio was shed (i.e., signal permanently disappeared). We evaluated a candidate set of 8 models, excluding sex and age from consideration because we had no biological reason to expect that retention would vary by those covariates. Our model set consisted of a null model and all combinations of day, species (surf scoter, white-winged scoter), and anchor type (single, double). We used identical criteria for model selection and covariate inference as described above, and retained identical reference values for our parameter estimates, with the addition that the estimate for species is the effect of white-winged scoters relative to surf scoters.

Survival.—We evaluated the daily probability of survival for radiomarked surf scoters as our second major comparison of single- versus double-anchor attachment techniques. Our survival analyses were limited to surf scoters because we detected no mortalities of white-winged scoters during molt (Uher-Koch et al. 2014), and we marked only surf scoters during winter. Previous research from sea ducks has shown that mortalities from capture, handling, and radio attachment are most likely to occur within the first 14 days (Esler et al. 2000, Hogan et al. 2013). Accordingly, our first survival analysis was restricted to the initial 14 days following attachment of radiotransmitters, with separate analyses for molt and winter periods. Our second survival analysis, however, excluded this initial 14-day period to examine more chronic and lagged effects of transmitter attachment on survival, and thus included telemetry data from day 15 to the end of our monitoring on day 134. We restricted this second analysis to the winter period because no mortalities were detected >14 days after transmitter attachment during molt (Uher-Koch et al. 2014). Moreover, we did not cap this analysis at 120 days from transmitter attachment because, as opposed to our analysis of transmitter retention, increasing rates of emigration from the study area in late winter would not bias our survival estimates. Specifically, missing transmitters, whether caused by emigration, transmitter failure, or transmitter shedding, were censored from our survival analyses following the date of last detection.

We used the nest survival model of Program MARK to estimate daily survival probabilities, coding our encounter histories for each individual as follows: 1) the day of transmitter attachment (i), scaled so that $i = 1$ for each individual; 2) the last day detected alive (j); 3) the last day the transmitter was monitored (k), and 4) the fate (f), where $0 =$ alive and $1 =$ dead. Birds that disappeared without an indication of mortality were censored from the database after the last day they were detected alive. We evaluated an identical set of 8 models for all survival analyses, consisting of a null model and all additive model combinations of sex, age, and anchor type. Additionally, for our analysis of days 1–14 during winter, we included a model with an interaction between age and anchor type to determine whether double-anchor attachments had a disproportionate effect on survival of immatures. Immature scoters typically have lower survival rates than adults, which may make them more vulnerable to additional subcutaneous anchors (Uher-Koch et al. 2016). This interaction term was not possible for our other survival analyses because of insufficient data for each age-by-anchor grouping. We used an identical approach to model selection and parameter inference as described above for our transmitter retention analyses, with the exception that $\sum w_i$ were not used to evaluate survival of wintering surf scoters during days 1–14 because each covariate in this model set did not appear in an equal number of models.

RESULTS

Transmitter Retention

Of the 110 radiotransmitters deployed on surf scoters during winter in southeastern Alaska, 40 had signals that disappeared during the 120-day tracking period. The best-fitting model to explain the daily probability that a radio signal was received during winter included only day as a covariate (Table 2). Day was strongly supported as having high explanatory value ($\sum w_i = 1.0$) and its parameter estimate (-0.02 ± 0.01) indicated that the daily probability of signal reception declined as winter progressed. All other models that received strong support ($\Delta \text{AIC}_c \leq 2$) had day as a covariate in combination with age, sex, and anchor type, although this support was driven almost exclusively by day; parameter estimates for age (-0.18 ± 0.51), sex (-0.11 ± 0.32), and anchor (-0.05 ± 0.32) were poorly estimated with SEs that widely overlapped zero, and all 3 covariates had $\sum w_i \leq 0.30$. Daily probabilities of signal reception were almost identical for radiotransmitters attached using single- versus double-anchor techniques (Fig. 1). The cumulative probability of signal reception for the 120-day study period was 0.51 ± 0.08 for single-anchor versus 0.49 ± 0.08 for double-anchor attachments.

Table 2. Model selection results assessing variation in 1) probability that transmitter signal was received for radiomarked surf scoters during winters of 2008 and 2009 in southeastern Alaska, USA, and 2) probability that transmitter was retained for radiomarked surf and white-winged scoters during the flightless remigial molt in Washington State, USA, and southeastern Alaska, 2008–2009. We report relative difference in Akaike's information criterion compared with the top-ranked model (ΔAIC_c), number of parameters (K), and AIC_c model weights (w_i), restricting our results to models with $\Delta \text{AIC}_c \leq 2$ and the null model. Covariates include Day (days since transmitter attachment), Age (immature, adult), Sex (male, female), Species (surf scoter, white-winged scoter), and Anchor (single-anchor, double-anchor).

Model	ΔAIC_c	K	w_i
Probability transmitter signal received in winter			
Day	0.00	2	0.36
Day + Age	1.69	3	0.16
Day + Sex	1.89	3	0.14
Day + Anchor	1.98	3	0.14
Null	10.32	1	0.00
Probability transmitter retained during molt			
Day + Anchor	0.00	3	0.48
Day	1.65	2	0.21
Day + Species + Anchor	1.97	4	0.18
Null	6.83	1	0.03

Radio signals disappeared for 14 of the 139 transmitters deployed on molting surf and white-winged scoters. We restricted our analysis to the flightless period, which extended up to 49 days from transmitter deployment; therefore, we interpreted these disappearing signals as shed transmitters. Day and anchor type were strongly supported by our model selection metrics; each covariate occurred in our best-fitting model (Table 2) and had $\sum w_i > 0.70$. Based on the best-supported model, the daily probability of transmitter retention was negatively related to day (-0.06 ± 0.02), progressively declining from transmitter deployment to recovery of flight. However, transmitter retention was improved by using a double-anchor attachment; the parameter estimate for anchor (1.08 ± 0.60) indicated that transmitters attached with 2 anchors had a greater probability of retention than those attached with a single anchor (Fig. 2). The cumulative probability of transmitter retention over the 49-day flightless period was 0.69 ± 0.11 for single-anchor and 0.88 ± 0.07 for double-anchor transmitters. Lastly, the species covariate was poorly estimated (0.10 ± 0.56) and received little support ($\sum w_i = 0.27$), indicating that retention rates were similar for surf and white-winged scoters.

Survival

Of the 110 transmitters deployed on surf scoters during winter, we censored 4 that were never detected and 13 where fate (mortality versus transmitter shedding) could not be clearly ascertained, leaving 93 individuals for our analysis of survival during the first 14 days following transmitter deployment. We detected 15 mortalities during this 14-day period, 11 of which had 2 subcutaneous anchors. The best-fitting model describing daily survival probability contained the covariates of age (-0.80 ± 0.53) and anchor (-1.15 ± 0.59), indicating that 1) scoters equipped with single-anchor transmitters had a greater probability of survival in the 14 days following capture and radiomarking

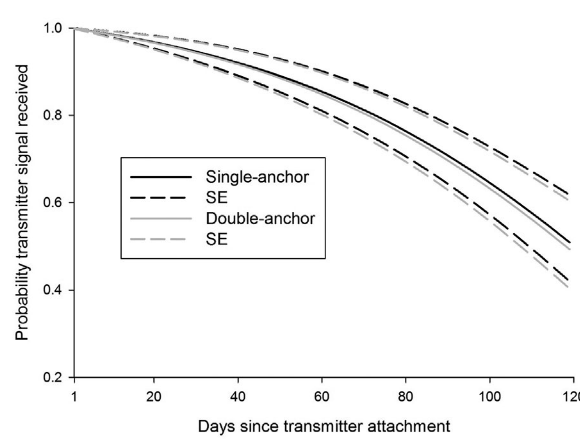

Figure 1. Daily probability that a radio signal was received (±SE) for radiotransmitters attached to surf scoters with single versus double subcutaneous anchors during winters of 2008 and 2009 in southeastern Alaska, USA.

than those equipped with double-anchor transmitters (Fig. 3), and 2) adults had a greater probability of survival than immature individuals during this same time period (Fig. 3). Four other models also received considerable support ($\Delta AIC_c \leq 2$), all of which contained anchor as a covariate (Table 3); no other covariates received this strong level of support. The covariate of sex received little support and was poorly estimated (-0.32 ± 0.53). Likewise, age × anchor (0.51 ± 1.31) was poorly supported, indicating no differential effects of anchor type on surf scoter age classes. Based on parameter estimates from our top-ranked model (Age + Anchor), cumulative survival rates for adults during the first 14 days following transmitter deployment were 0.94 ± 0.04 for single-anchor versus 0.82 ± 0.07 for double-anchor attachments; for immature birds, these same rates were 0.87 ± 0.07 for single-anchor versus 0.64 ± 0.11 for double-anchor attachments.

During remigial molt, we detected 8 mortalities among 92 surf scoters and 0 mortalities among 47 white-winged scoters in the first 14 days following transmitter attachment. Of these mortalities, 3 occurred in Washington State and 5 in southeastern Alaska. The best-fitting model to explain daily survival probability over this 14-day period was the null model (Table 3), which fit only an intercept, suggesting that our covariates had little explanatory power. Parameter estimates for age (-0.55 ± 0.73) and sex (0.09 ± 0.71) were poorly estimated with SEs that widely overlapped zero. Likewise, anchor type was poorly estimated (-0.50 ± 0.73), indicating little difference in survival probability for single- versus double-anchor attachments in the 14 days following transmitter deployment on molting scoters (Fig. 4).

Seventy-three wintering surf scoters were available for radiotracking after censoring individuals that died or disappeared during the first 14 days following transmitter deployment. Of these, we detected 13 mortalities over the remainder of winter, which spanned from 15 to 134 days after transmitter deployment. Age was included in all 3 of the best-fitting models (Table 3) and was the only covariate that received substantial support ($\sum w_i = 0.87$). The parameter estimate for age (-1.44 ± 0.66) indicated that adults had greater daily survival probabilities than did immature individuals (Fig. 5). Conversely, covariates of sex (-0.02 ± 0.56) and anchor type (-0.05 ± 0.58) had small parameter estimates with large standard errors, and $\sum w_i <$ 0.30. Accordingly, for days 15 to 134 following transmitter deployment, daily and cumulative survival probabilities were nearly identical for single- versus double-anchor attachments (Fig. 5).

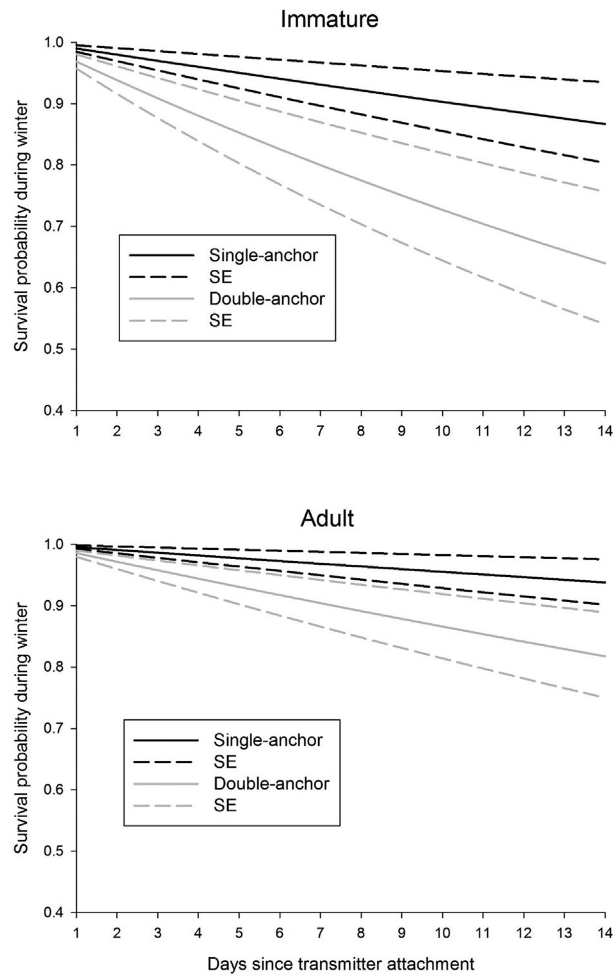

Figure 3. Daily probability of survival (±SE) for immature and adult surf scoters carrying radiotransmitters attached with single versus double subcutaneous anchors during winters of 2008 and 2009 in southeastern Alaska, USA. Survival probabilities are limited to the first 14 days following transmitter attachment, when transmitter-associated mortalities are most likely to occur.

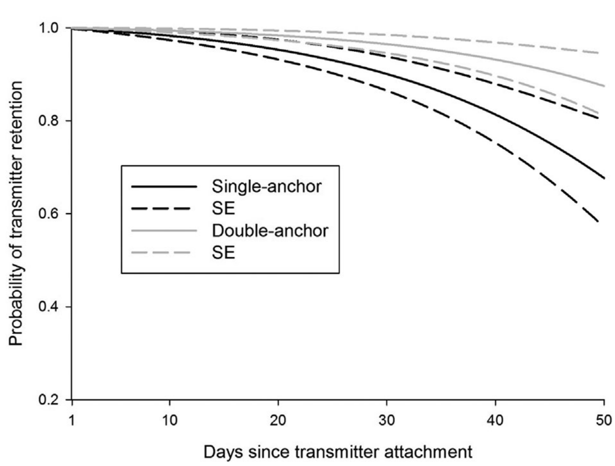

Figure 2. Daily probability of transmitter retention (±SE) for radio-transmitters attached to surf and white-winged scoters with single versus double subcutaneous anchors during the flightless remigial molt in Washington State and southeastern Alaska, USA, 2008–2009.

DISCUSSION

Compared with transmitters attached to scoters with a single anchor, those attached with double anchors had longer retention times but resulted in lower postattachment survival of scoters. These differences could not be attributed to transmitter type or bird handling procedures—we used identical transmitter packages, capture methods, and holding facilities for all radiomarked birds, irrespective of attachment

Table 3. Model selection results assessing variation in 1) daily survival probability in the first 14 days since transmitter attachment for surf scoters in southeastern Alaska, USA, during winters of 2008 and 2009; 2) daily survival probability in the first 14 days since transmitter attachment for surf scoters during the flightless remigial molt in Washington State, USA, and southeastern Alaska, 2008–2009; and 3) daily survival probability of surf scoters for days 15–134 since transmitter attachment during winters of 2008 and 2009 in southeastern Alaska. We report relative difference in Akaike's information criterion compared with the top-ranked model (ΔAIC_c), number of parameters (K), and AIC_c model weights (w_i), restricting our results to models with $\Delta AIC_c \leq 2$ and the null model. Covariates include Age (immature, adult), Sex (male, female), and Anchor (single-anchor, double-anchor).

Model	ΔAIC_c	K	w_i
Survival probability: winter days 1–14			
Age + Anchor	0.00	3	0.25
Anchor	0.32	2	0.21
Sex + Age + Anchor	1.63	4	0.11
Age + Anchor + Age × Anchor	1.86	4	0.10
Sex + Anchor	1.97	3	0.09
Null	2.07	1	0.09
Survival probability: molt days 1–14			
Null	0.00	1	0.33
Age	1.47	2	0.16
Anchor	1.52	2	0.16
Sex	1.99	2	0.12
Survival probability: winter days 15–134			
Age	0.00	2	0.46
Age + Anchor	1.99	3	0.17
Sex + Age	2.00	3	0.17
Null	3.78	1	0.07

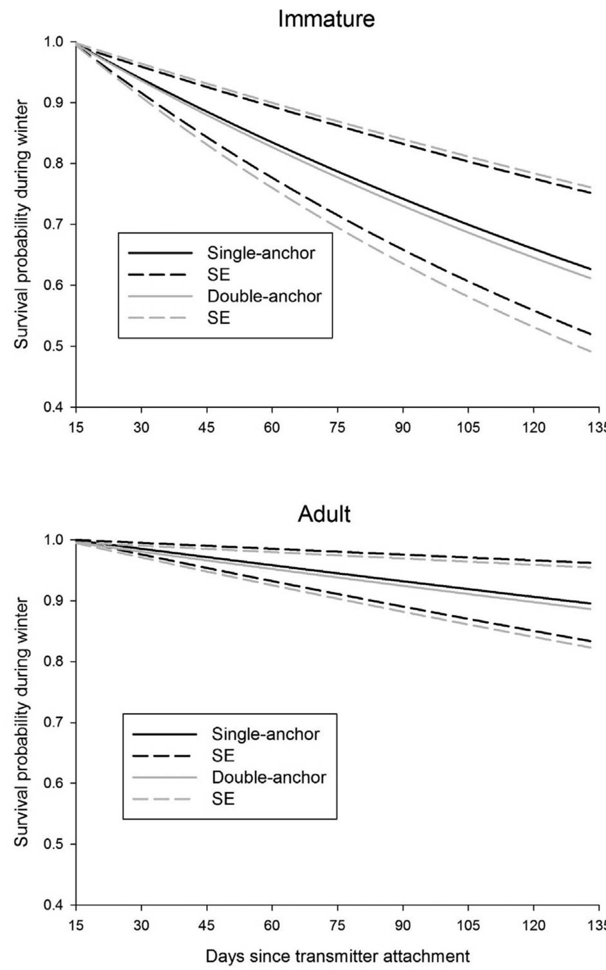

Figure 5. Daily probability of survival (±SE) for immature and adult surf scoters carrying radiotransmitters attached with single versus double subcutaneous anchors during winters of 2008 and 2009 in southeastern Alaska, USA. Survival probabilities are for days 15–134 following transmitter attachment, when transmitter-associated mortalities are expected to decline and natural mortalities predominate.

technique. Moreover, by capturing and handling all birds equally, our study design essentially singled out the survival cost of a subcutaneous anchor, which can be considered as the difference in survival between single- versus double-anchor attachments. Accordingly, researchers must carefully weigh the costs and benefits of attaching transmitters using 1 versus 2 subcutaneous anchors, or choosing a different attachment technique altogether, such as harnesses, tape, or internal implantation (Iverson et al. 2006).

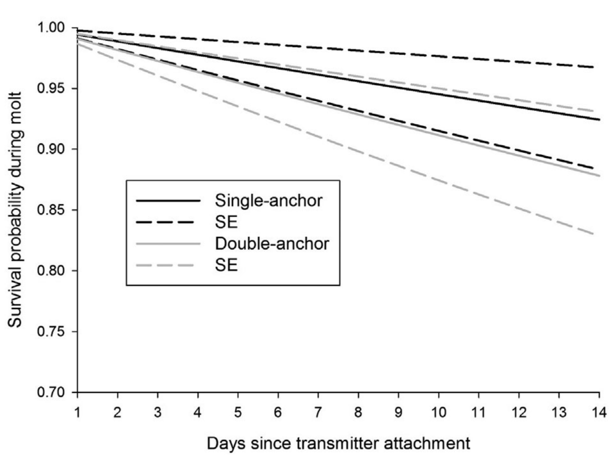

Figure 4. Daily probability of survival (±SE) for surf and white-winged scoters carrying radiotransmitters attached with single versus double subcutaneous anchors during the flightless remigial molt in Washington State and southeastern Alaska, USA, 2008–2009. Survival probabilities are limited to the first 14 days following transmitter attachment, when transmitter-associated mortalities are most likely to occur.

We used transmitter retention as our first major criterion of attachment efficacy for single- versus double-anchor attachments. Transmitter retention rates have been generally difficult to estimate for sea ducks, mainly because researchers cannot reliably distinguish between the 2 primary causes of radio signal disappearance—transmitter shedding versus emigration from the study area. Shed transmitters are generally deposited in the ocean, where their signals are attenuated, whereas sea ducks that emigrate from the study area following transmitter attachment are rarely detected (Iverson et al. 2006). Nonetheless, we were able to estimate accurate rates of transmitter retention by attaching transmitters to scoters during the flightless remigial molt, thereby eliminating the possibility that radio signals disappeared because of emigration. Our results indicated that addition of a second anchor improved radio retention over a 49-day period for molting scoters, increasing the cumulative retention probability from 0.69 for single-anchor to 0.88

for double-anchor attachments. Previously reported retention rates for single-anchor attachments have been highly variable, ranging from lows of 0.55, where 20 of 42 northern shovelers (*Spatula clypeata*) lost their transmitters over 30 days (Zimmer 1997), to highs of 0.98, where only 2 of 93 mallards (*Anas platyrhynchos*) and gadwalls (*Mareca strepera*) lost their transmitters over 75 days (Pietz et al. 1995). In light of such high variability in retention rates for single-anchor attachments, including some inadequately low rates, our results indicate that retention can be reliably improved, with minimal to no effect on transmitter mass and size, by adding a second subcutaneous anchor.

We also evaluated transmitter retention for surf scoters during winter, finding that, contrary to the molting period, retention did not appear to differ for single- versus double-anchor attachments. This apparent discrepancy in transmitter retention between molt and winter is likely attributable to 2 primary causes. First, because scoters were flighted during winter, our metric of transmitter retention—the probability of radio signal reception—was extremely coarse, being unable to differentiate transmitters that were shed from those that failed or emigrated from the study area. This is especially problematic for sea ducks because they may emigrate long distances in short periods of time and often use habitats that are unavailable to shore-based telemetry systems (Latty et al. 2010). As a result, the resolution of our telemetry data may have been too poor to detect differences in transmitter retention for single- versus double-anchor attachments during winter. Second, during the remigial molt, feather sheaths, integument, and other epidermal structures are regenerated over the entirety of the body, including the middorsal region of transmitter attachment (Savard and Petersen 2015). This process of regeneration, in combination with the frequent preening of newly emerging feathers (Portugal et al. 2010), may accelerate transmitter shedding for molting scoters. Under such circumstances, a second anchor may have a stronger positive effect on retention than during other periods of the year, potentially explaining our observed differences in apparent retention between winter and molt.

In addition to transmitter retention, a primary consideration when choosing an appropriate transmitter attachment technique is the welfare of the study animal, which we assessed using daily survival probabilities. We documented significantly lower survival rates of wintering surf scoters with 2 versus 1 subcutaneous anchors during the first 14 days following transmitter attachment; of 15 mortalities during this period, 11 had 2 subcutaneous anchors. From day 15 onward, however, survival rates were nearly identical for single- versus double-anchor attachments. Recent research on long-tailed ducks (*Clangula hyemalis*) affixed with transmitters using 2 subcutaneous anchors provides some insight into possible causes of mortality—within 2 days of attaching transmitters to 5 birds, 1 died due to a bacterial infection that originated at the anchor insertion site, while a second individual developed an elevated white blood cell count that required antibiotic treatment (Enstipp et al. 2015). These patterns suggest that 1) adverse effects of subcutaneous anchors on survival are mainly restricted to the 14-day postattachment period, after which natural mortality predominates; 2) increased mortality may be a direct result of infection resulting from subcutaneous anchors; and 3) the double-anchor technique may represent a functional doubling of infection risk over the single-anchor approach, leading to greater mortality rates for birds carrying 2 subcutaneous anchors.

In contrast to the winter period, survival during remigial molt did not differ for single- versus double-anchor attachments in the 14 days following radiomarking. Moreover, mortality rates in general, irrespective of attachment technique, were considerably lower for molting scoters; 6% of molting versus 14% of wintering scoters died in the 14-day postattachment window, whereas 0% of molting versus 18% of wintering birds died from day 15 onward (Uher-Koch et al. 2014). If attachment-induced mortalities were entirely attributable to bacterial infections, as discussed above, then we would have expected comparable survival rates for wintering versus molting scoters, especially during the 14 days following transmitter attachment. Instead, wintering birds may have been more vulnerable to predation and poor body condition because of transmitter-induced changes to their behavior. Namely, transmitters disturb plumage and increase heat loss, causing birds to exit the water to preen and thermoregulate (Perry 1981, Barron et al. 2010). Enstipp et al. (2015) observed that wintering long-tailed ducks, upon attachment of transmitters with subcutaneous anchors, reduced their time spent in the water by nearly 50% while concomitantly increasing their preening time by 98–150%; these changes were most pronounced immediately after radiomarking. During winter, when colder conditions prevail, radiomarked scoters may have exhibited unusual behaviors such as hauling out to preen their feathers and thermoregulate. Such behavioral changes would decrease attentiveness to predators and lessen the utility of diving as an escape mechanism, thereby increasing their vulnerability to both avian and terrestrial predators (Rosenberg and Petrula 2000, Iverson et al. 2006). Additionally, more time spent hauled out and preening may disproportionately compromise body condition and, by extension, survival of scoters during winter, mainly because shorter day lengths provide less flexibility to compensate for lost foraging time while colder temperatures raise energy demands. During molt, however, radiomarked scoters likely exited the water much less, primarily because temperatures were warmer and, lacking the ability to fly, they relied almost exclusively on diving for predator avoidance (Dickson et al. 2012). As such, radiomarked scoters may have been less susceptible to predators and poor body condition during remigial molt, contributing to their greater observed survival during this period. Moreover, in contrast to winter when all of our transmitters were deployed in Alaska, we deployed 35 of 139 transmitters in Washington State during the remigial molt. Previous research with surf scoters has shown that, during winter, survival was lowest at the northern periphery of their winter range in Alaska, due in part to greater predator densities and more extreme climatic conditions at these latitudes (Uher-Koch et al. 2016). Accordingly, the milder climate and lower predator densities at our Washington State study site, which was nearly 10° lower in latitude, may have partially contributed to the greater observed survival of molting relative to wintering scoters.

MANAGEMENT IMPLICATIONS

Overall, our study documented an important trade-off for transmitters attached with single- versus double-anchor techniques—addition of a second subcutaneous anchor increased transmitter retention, but at the cost of reduced survival. Given that this survival cost was quite substantial—decreasing 14-day survival of wintering surf scoters by 12% for adults and 23% for juveniles—we recommend that researchers use a single subcutaneous anchor for attaching transmitters to waterfowl and other birds. Moreover, because mortalities for both single- and double-anchor attachments were especially elevated in the 14 days following transmitter attachment, we advise that researchers censor survival data from this period when attempting to estimate natural survival rates. Researchers may also consider adding an antibacterial treatment to the incision site following transmitter attachment. Although we recommend single-anchor attachments, this method is primarily intended for relatively small and lightweight transmitters. Some large transmitters may require a second anchor to secure their posterior ends, thus preventing undue strain on a single anchor and premature transmitter shedding (Lewis and Flint 2008). Lastly, our winter mortality rates were greater than other avian studies that attached transmitters with subcutaneous anchors. This may be explained, in part, by the general sensitivity of our study species to transmitter attachment, and the unusually high density of predators, particularly bald eagles (*Haliaeetus leucocephalus*), at our southeastern Alaska study site. Several other studies documented unusually high mortality rates for radiomarked surf and white-winged scoters in Alaska, including 43% for scoters with surgically implanted transmitters (Rosenberg and Petrula 2000). Accordingly, other researchers should not assume that our mortality rates will apply to their study species and study systems when attaching transmitters with subcutaneous anchors, only that the overall risk of mortality appears to increase with addition of a second anchor.

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