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Entanglement-scar acquisition rates and scar frequency for Bering-Chukchi-Beaufort Seas bowhead whales using aerial photography

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Abstract

The Bering-Chukchi-Beaufort Seas (BCBS) bowhead whale (*Balaena mysticetus*) has been considered at low-risk for entanglement injuries and ship strikes because their range is mainly north of commercial fisheries; nevertheless, changes to their arctic habitat, including a longer open water period and declining sea ice, have resulted in increasing commercial activity and concern about fisheries interactions. We examined interyear matches (between 1985 and 2011) from a photo identification project and identified whales that had acquired entanglement injuries. We estimated the probability of a bowhead acquiring an entanglement injury using two statistical methods: interval censored survival analysis and a simple binomial model. Both methods give similar results, suggesting a 2.2% (95% CI: 1.1%–3.3%) annual probability of acquiring a scar. We also include an entanglement scar frequency analysis of aerial photographs from the 2011 spring and fall surveys near Point Barrow, Alaska, which suggest 12.4% of live bowheads show evidence of entanglement scarring. Entanglement rates for the BCBS bowhead stock are lower than many other large whale stocks, and abundance has increased over the past 35 yr; however, our findings indicate that fishing gear entanglement is a more serious concern for the BCBS bowhead whale population than previously thought.

Key words: bowhead whale, *Balaena mysticetus*, Arctic, marine mammal, entanglement, injury, scarring, aerial survey, photo-identification, bycatch.

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The circumpolar habitat of the Bering-Chukchi-Beaufort Seas (BCBS) bowhead whale (*Balaena mysticetus*) is experiencing rapid climate warming, leading to a longer open water period and declining sea ice, resulting in more industrial activity, shipping, tourism, and expanding commercial fisheries across the Arctic (Reeves *et al.* 2012). These changes are increasing the potential for interaction between bowheads and fisheries gear (Moore and Reeves 1993, Moore *et al.* 2004, Read *et al.* 2006, Reeves *et al.* 2012, Citta *et al.* 2013), despite the fact that the bowhead winter range has been mainly north of most commercial fisheries. George *et al.* (2017) reported 12.2% of carefully examined bowhead whales harvested by Alaska Native hunters between 1990 and 2012 showed evidence of entanglement scarring, but there was no statistically significant increase in injuries through that period. Here we expand previous studies of bowhead entanglement in order to better understand the magnitude of the problem, provide a baseline for future assessments, and help guide management efforts in the U.S. arctic region.

The International Whaling Commission Scientific Committee has identified bycatch as "the single greatest threat to cetaceans from human activities globally" (IWC 2017). Read *et al.* (2006) estimated the global bycatch of cetaceans to be 308,000 annually. Numerous studies have used photographic databases to analyze evidence of entanglement scarring in large whales (Kraus 1990; Robbins and Mattila 2001, 2004; Knowlton *et al.* 2012; Robbins *et al.* 2015). The endangered North Atlantic Right Whale (NARW), a close relative of the bowhead, similar in body shape, numbers approximately 450 individuals (Pace *et al.* 2017) and has particularly high rates of entanglement (Knowlton *et al.* 2012, Robbins *et al.* 2015). Knowlton *et al.* (2012) found 82.9% of NARW experience an entanglement injury during their lifetime, with 59.0% entangled on multiple occasions and 25.9% of the adequately photographed right whales entangled annually. In a photographic study of humpback whales in Southeast Alaska, Neilson *et al.* (2009) reported the percentage of nonlethal entangled animals ranged from 52% to 78% depending on their confidence that the scars were caused by entanglement. In a similar study of Gulf of Maine humpback whales, Robbins (2012) estimated that 16.9% of whales exhibited new scarring over a 1 yr period. Robbins (2012) also reported considerably higher entanglement scarring rates for juveniles.

In spring 2011, Givens *et al.* (2018) conducted an aerial photo identification (photo-ID) survey near Point Barrow, Alaska, to estimate survival rates and abundance of the BCBS bowhead stock; however, anthropogenic scars and injuries from entanglements, ship strikes, and attached gear were also noted in the photographs. Whereas past assessments of entanglement scars on bowheads have been applied only to whales harvested by Alaskan Eskimos, here we use the results of the aerial survey to assess the frequency of entanglement scars on *live* bowheads. Further, we used the large sample of matched photographs from the survey of live whales obtained between 1985 and 2011, as reported by Givens *et al.* (2018), to estimate scar acquisition rates.

Methods

The study had two main objectives: (1) analyze the photo-ID interyear mark-recapture matches to estimate a scar acquisition rate (*i.e.*, annual probability) for BCBS bowheads, and (2) evaluate the 2011 survey photos for evidence of entanglement, including a photo quality assessment, to estimate the proportion of individuals with entanglement scarring. To address the first objective, we used a data set of interyear matched whales for 1985, 1986, 2003, 2004, 2005, and 2011 (Givens *et al.* 2018). To address the second objective, we examined photos taken near Utqiaġvik (Barrow), Alaska, during the 2011 spring and fall aerial surveys (19 April to 6 June in 2011 and 27 August to 16 September 2011).

Aerial survey methodology was identical for both objectives and similar to earlier photogrammetric studies (Koski *et al.* 1992, Angliss *et al.* 1995). The 2011 spring and fall surveys were flown in the region northeast of Utqiaġvik, Alaska. The aircraft flew at altitude of 200 m (656 ft) in most years, directly over bowhead whales during photographic passes. Photographs in 2011 were taken with a handheld Canon Mark III-1DS digital camera affixed with a Zeiss 85 mm fixed f/1.4 Planar T* lens pointed directly downward through the aircraft's ventral camera port, which was covered with optical quality glass. Field protocols for pre-2011 data (1985, 1986, 2003, 2004, and 2005) have been documented in detail (Angliss *et al.* 1995; Koski *et al.* 1992, 2006, 2010; Rugh *et al.* 1992, 1998). When available, each image was accompanied by an estimated photogrammetric whale length (m) (Koski *et al.* 2006).

The data set of interyear matches was comprised of whales that were photographed in at least two different years among 1985, 1986, 2003, 2004, 2005, and 2011. The fall 2011 surveys were conducted during the bowhead feeding study (BOWFEST) (Shelden and Mocklin 2013). Each of these matches enables us to assess whether a scar had been acquired in the interval between the two sightings. Givens *et al.* (2018) describe in more detail the photo-ID capture-recapture data set used to generate data for the present study.

Bowheads were individually identified by natural dorsal scars (mostly sea-ice inflicted) on their bodies following standard photo identification protocols (Rugh *et al.* 1992). It is worth noting that the bowhead scars seen in aerial photos were remarkably persistent through the 26 yr time span of this study, allowing their photographic recapture. We also note that the bowhead photographic catalog is biased towards late subadult and adult whales as it takes considerable time to acquire ice-inflicted scars. In previous studies on landed whales, George *et al.* (1994, 2017) provided evidence that line-wrap marks on the caudal peduncle, notches at the fluke-insertion point, scarring along the fluke leading edge, and tissue damage in the peduncle region are primarily inflicted by commercial fishing operations.

The methods used for scoring photo quality and whale identifiability based on four body zones (mid-back, lower-back, rostrum, flukes) are described at length by Rugh *et al.* (1992, 1998). Details of the photo-ID process were reported by Mocklin *et al.* (2015) and Vate Brattström *et al.* (2016). It is important to note the standard photo-ID protocol does *not* include the peduncle region; therefore, a second photo quality evaluation was conducted for our analysis focusing on the caudal peduncle. Image quality was scored as either adequate for evaluation or inadequate due to low photo quality and/or obstructed view of the peduncle region. If the photo was coded as having inadequate quality, it was not examined for scarring. Similar to photo-ID mark-recapture studies, judgments of photo quality are subjective and based on experience viewing aerial photographs. To maximize consistency of this subjective assessment, the same person performed the analysis for all images and a second analyst reviewed all assessments. The scoring of photo quality was limited to the peduncle and fluke insertion point, since this region is the most likely to be entangled based on examinations of harvested whales and the resulting scars are detectable in suitable aerial photographs. To be scored as adequate, the visibility of the peduncle could not be seriously compromised by ice, splash, fog, glare, reflections, blur, submersion, or mud on the whale. Visibility could be slightly compromised and still be considered adequate, but large, medium, and some small marks needed to be visible (Rugh *et al.* 1992). For each individual, all available images were viewed, including supporting images, in case they provided a clear view of the peduncle.

The criteria for designating an entanglement interaction were the following: (1) scars wrapping over or around the caudal peduncle, including linear and/or curvilinear scarring; (2) marks, notches, and/or tissue damage at the insertion point; and (3) scarring and notches on the leading edge of the flukes that appeared to be associated with entanglement scarring on the peduncle (Fig. 1). Even "adequate" aerial photos can present challenges for the evaluation of scarring due to distortion and distance. To account for varying degrees of certainty, confidence scores were recorded for whales found to have evidence of entanglement scarring. "High" confidence (>90%) was recorded for multiple linear and/or curvilinear marks on the peduncle and fluke insertion point, often accompanied by serious tissue damage and entanglement-related scar patterns. "Probable" confidence (>70%–90%) was scored for clear linear and/or curvilinear marks observed in the region of the peduncle and/or fluke insertion point, appearing to be entanglement-related scarring. "Moderate" confidence (50%–70%) was recorded for one or two linear or curvilinear marks on the peduncle and/or fluke insertion point that appeared to be entanglement-related.

Entanglement Scar Acquisition Rate

Interyear matches found during the mark-recapture study (Givens *et al.* 2018) were evaluated to determine whether a whale had acquired an entanglement injury (Fig. 2). Pre-2011 images used for the abundance study were from the BCBS bowhead photographic catalog[2] used in previous population estimates (Rugh 1990, da Silva *et al.* 2000, Koski *et al.* 2010). During the photo-ID study, standard protocols were applied to

[2]Maintained by the North Slope Borough, Barrow, AK; LgL Canada, King City, Ontario, CA; and the NOAA-NMFS Marine Mammal Laboratory, Seattle, WA.

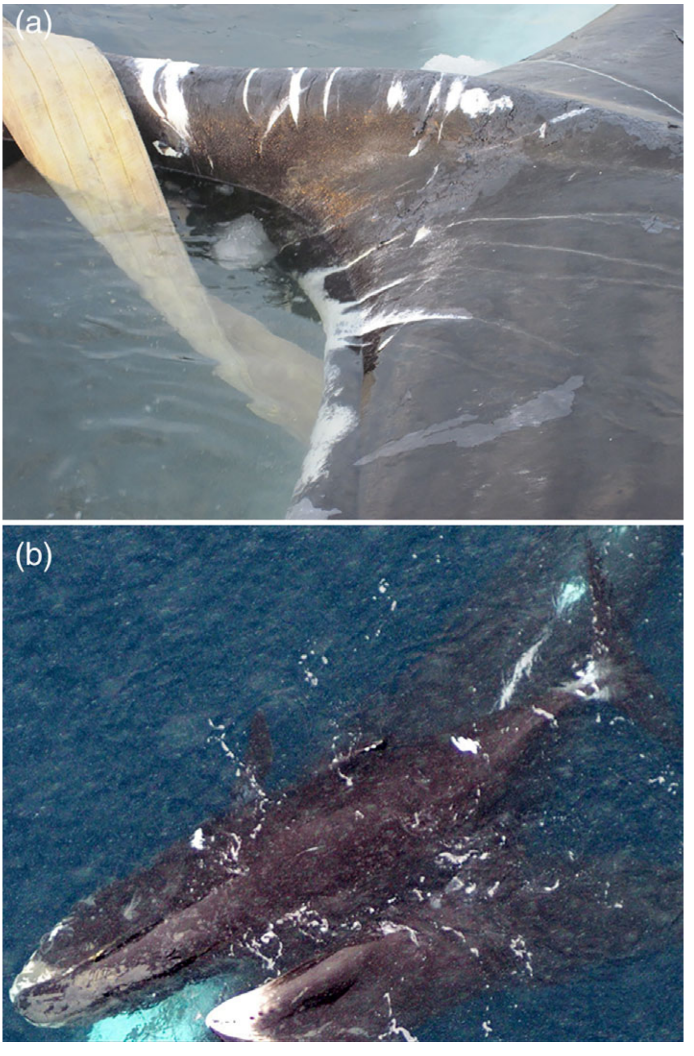

Figure 1. Photographs of entanglement injuries to (a) the peduncle on a harvested whale (11B5; 16.0 m, female, landed at Barrow, Alaska), and (b) a large adult photographed during the 2011 aerial survey (01161407.03) showing entanglement injuries scored as "High" confidence. Note that injuries on whale 11B5 involve the junction and leading edge of the flukes as well as the peduncle. Examinations of harvested whales provide an important opportunity for studying entanglement injuries. Photo credit: (a) NSB Department of Wildlife Management (Permit 17350), (b) NSB-MML 2011 aerial photo survey taken under Scientific Research Permits 782-1719 and 14245 issued to MML under the provisions of the US Marine Mammal Protection Act and Endangered Species Act.

match the 2011 aerial photographs with all years (1985, 1986, 2003, 2004, 2005, and 2011) (Rugh 1990, Rugh *et al.* 1992). In addition, researchers matched 2003, 2004, and 2005 with 1985 and 1986, thereby

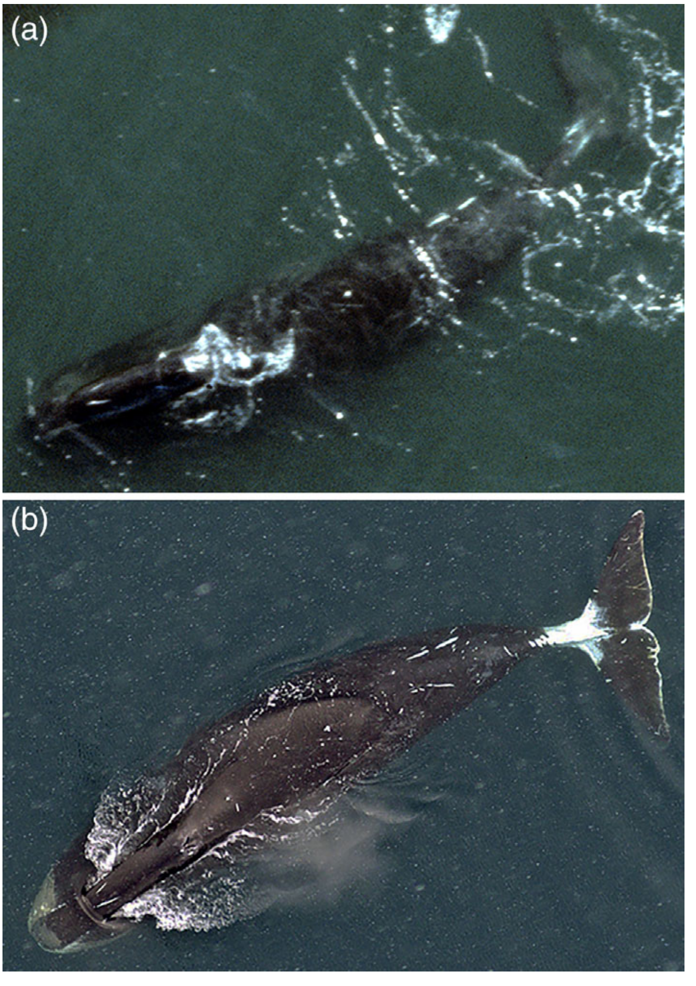

Figure 2. Aerial images of an inter-year match of a whale photographed in (a) 1985 without entanglement scarring, and (b) photographed in 2011, 26 yr later with entanglement scars, scored as high confidence. With regard to photo (b), the bowhead peduncle has "whitened" with age; however, clear entanglement injuries are evident anterior to the white patch. Furthermore, some of the white on this animal's peduncle, leading edge of the flukes, and fluke notch is likely from the entanglement injury. Photo credit: (a) LGL Limited/MML; (b) NSB-MML 2011 aerial survey (whale 01163400). Taken under Scientific Research Permits 782-1719 and 14245 issued to MML under the provisions of the US Marine Mammal Protection Act and Endangered Species Act.

creating a complete set of matched photos from these 6 yr. A total of 117 interyear reidentifications were found, which provided an opportunity to evaluate entanglement scarring over a span of 26 yr.

Only whales that were unscarred (in the peduncle region) at the first photo capture, and either unscarred or scarred in a subsequent recapture, with adequate photo quality in each were used for this analysis

(n = 68). The data were aligned so that the calendar year of first photo capture was defined to be year 0.

Our first analysis approach was nonparametric interval-censored survival analysis that was fit *via* maximum likelihood (Turnbull 1976, Gentleman and Geyer 1994). Survival analysis pertains to time-to-event data, and traditionally the event is death of the patient in a clinical trial. The concept of (right) censoring means that the event is not always observed, *e.g.*, because the clinical trial ended before the patient died. In our case, the event is scar acquisition. For our bowhead data, censoring occurs for many whales because they have not yet been recaptured at a time after a scar has been acquired. There is important information in such data: although we do not know the time to acquisition, we do know that the time exceeds the observation period. The bowhead data are more complex than this—the data are actually interval censored. This type of censoring occurs when one only observes whether the event (scarring) has occurred yet, at a series of observation times. Interval censoring is comprised of both right censoring and left censoring, where the latter occurs because we do not know when the whales were first exposed to potential scar acquisition. Finally, it is worth emphasizing that for survival analysis the event does not need to be inevitable. The model and analysis are sometimes called "time-to-event" to emphasize this point; events like divorce, criminal recidivism, and whale scarring are such examples. The goal of the survival analysis is to provide information about risk over time, regardless of whether the event must happen eventually.

The data for interval censored survival analysis are comprised of the last time each whale was seen unscarred and the first time when each was seen scarred. If a recaptured whale was never seen scarred, the first time of scarring is noted as right censored because it hasn't happened yet at the time of last capture. As explained above, both uncensored and censored cases are included in the analysis. We use the *interval* package in R to fit the statistical model (Fay and Shaw 2010). Uncertainty of the fit was estimated using the bootstrap, with 1,000 samples, as implemented in that package.

The second analysis was based on a binomial model. The time frame from capture to recapture constituted one trial. Unlike the survival analysis, in this case we consider all intercapture intervals, not just the interval from the first to last sighting of each animal. Let y_i denote the length of the ith interval, in years. Let p denote the annual probability of acquiring a scar. Then, under independence assumptions, the probability of acquiring a scar after y_i years is $s_i = 1 - (1-p)^{y_i}$ and the binary outcome of a trial evidencing a scar has the distribution Bin(1, s_i). From this, a joint likelihood function for the data can be generated, and we maximized this to estimate p. The variance of the estimated p was estimated using the Hessian in the standard manner. We comment further on this approach in the Discussion.

Frequency of Whales with Entanglement Injuries in 2011

We examined both spring and fall 2011 aerial photos (n = 2,198) taken near Point Barrow, Alaska, to estimate the proportion of whales with entanglement scars, limiting the set of whales to only those with adequate

Table 1. Sample sizes for the 2011 aerial photographic survey near Point Barrow, Alaska, and scar frequency analysis.

Statistics	N
Total raw images of whales	6,801
Total individual whales (after completing within year matching)	2,198
Total whales with adequate photo quality of caudal peduncle	692
Number and percentage of whales with entanglement scars (2011)	86 (86/692 = 12.4%)

photo quality of the peduncle region (n = 692) (Table 1). The individuals with suitable photographic coverage of the peduncle region were then evaluated for entanglement scarring, and the observed scars were assigned the confidence scores described earlier (High, Probable, Moderate). Scar frequency for 2011 was calculated as a simple percentage of adequately photographed whales with entanglement scarring in the sample.

Results

Entanglement Scar Acquisition Rate

We examined a total of 117 matched whales (captures and recaptures) ranging from 1985 to 2011. After excluding low quality images and whales that were scarred in all photographed years, matched sightings of 68 whales were available for analysis. Of these, 15 (21%) whales had acquired scars (Table 2). In addition to rope scarring, two whales were photographed carrying fisheries gear (0.3%) and seven whales were scored for ship-inflicted scarring (1%).

The average time elapsed for the 15 whales that acquired entanglement scars was 17.6 yr. The average length of whales in the data set when first photographed (where photogrammetric lengths were available) was 12.6 m (SD = 1.75 m, n = 14) and 14.2 m (SD = 1.7 m, n = 15) when rephotographed (Table 3). These lengths are roughly

Table 2. Sample sizes for entanglement scar acquisition rate analysis of interyear photo-ID matches.

Statistic	N
Total interyear recaptures evaluated for entanglement scarring	117
Total whales *excluded* because of low photo quality and/or whale scared in both occasions	49
Total interyear recaptures with adequate photo quality; not scarred on at least one occasion	68
Total interyear recaptures with change in entanglement scarring	15

Table 3. Statistics for whales that have acquired entanglement scars during the 26 yr study period (1985 to 2011). Init. Yr = initial year the whale was photographed; BL 1 = photogrammetric body length (m) of whale when first photographed; Scar 1 = was whale scarred in first photograph? (Y/N); Recap. Yr = year the whale was photographically recaptured; BL 2 = body length (m) of whale when recaptured; Scar 2 = was the whale scarred in recapture? (Y/N); Conf. score = confidence that whale had an entanglement scar (M = Moderate, P = Probable, H = High); Time span = number of years between photographic capture and recapture.

Init. Yr	BL 1 (m)	Scar 1	Recap. Yr	BL 2 (m)	Scar 2	Conf. score	Time span
1985	10.4	N	2003	14.4	Y	P	18
1985	10.4	N	2003	13.9	Y	M	18
1985[a]	10.5	N	2003	10.9	Y	P	18
1985	13.4	N	2011	NA	Y	H	26
1985	13.5	N	2011	14.9	Y	P	26
1985	12.0	N	2011[b]	16.3	Y	H	26
1986	NA	N	2003	13.0	Y	P	17
1986	16.2	N	2003	17.2	Y	H	17
1986	13.4	N	2004	14.0	Y	P	18
1986	13.5	N	2011	15.0	Y	M	25
1986	11.1	N	2011	13.1	Y	P	25
2003	13.8	N	2011	14.5	Y	P	8
2003[c]	11.6	N	2011	12.7	Y	P	8
2004	14.6	N	2011	16.1	Y	M	7
2004	12.0	N	2011	15.0	Y	P	7

[a]Also seen unscarred in 1986.
[b]Whale shown in Figure 2b with High Confidence entanglement scar.
[c]Also seen unscarred in 2004.

correlated with whales in their late teens to mid-twenties respectively as the mean length at sexual maturity is estimated to be ~13.5 m at about 25 yr for females and about the same age or slightly earlier for males (George *et al.* 1999, Rosa *et al.* 2013).

The survival analysis estimate (Fig. 3, solid black line) shows how the probability of acquiring a scar over a period of time is estimated to depend on the duration (*i.e.*, elapsed years) of that period. The gray shaded boxes represent regions where no estimate is possible because there are no elapsed periods of the corresponding duration. This occurs because the only observed time lapses are those between the set of years 1985, 1986, 2003, 2004, 2005, and 2011, in their various combinations. The faint gray lines show 95% confidence bands for the estimated function.

The result of the binomial model is an estimate for p, the annual probability of acquiring a scar. We estimate $p = 0.022$, with 95% confidence interval (0.011, 0.033). Using the model described above, we can project that estimate, and its confidence bounds, forward in time. In Figure 3 the solid blue line (*i.e.*, the smooth curve) indicates the probability of an individual bowhead acquiring a scar increases over time, and the blue dashed lines are the confidence bounds. The cumulative probability of

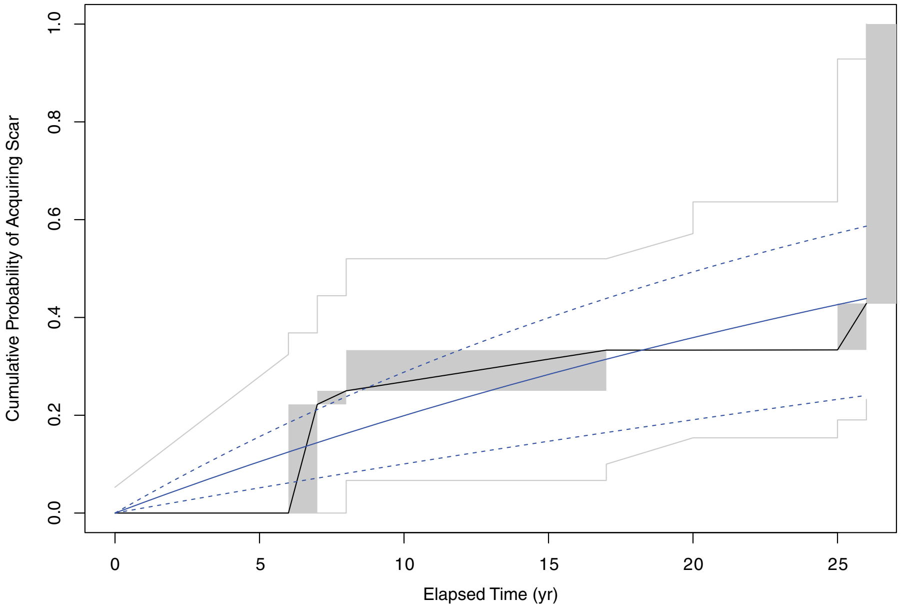

Figure 3. Estimated cumulative probability of obtaining an entanglement scar over an elapsed number of years. The (jagged) black and gray lines represent the results of the interval censored survival analysis. The black line is the estimated curve, the faint gray lines are 95% confidence bands, and the gray shaded boxes are indeterminate regions due to data sampling granularity. The smooth blue curves correspond to the estimated cumulative probabilities (solid) and 95% confidence limits (dotted) for the binomial analysis.

acquiring a scar is estimated to be 20% over an elapsed time of 10 yr, and 43% over a period of 25 yr.

Proportion of Whales with Entanglement Injuries 2011

It is important to note that the proportion of entanglement scarring in 2011, *i.e.*, the prevalence, is distinct from the scar acquisition rate. The 2011 aerial photos collected as part of the photo-ID study provided a total of 4,594 aerial photos containing 6,801 bowhead whales (not accounting for resightings). After within-year matching of spring and fall 2011, 2,198 uniquely identified bowhead whales (including 72 calves) were found. These 2,198 photos of individual whales were used to analyze entanglement scar frequency of whales photographed in 2011. After scoring photo quality of the peduncle region, we had 692 adequate photos of individual whales specifically for evaluating entanglement scarring. Of these, 86 whales (12.4%) had evidence of entanglement injuries (Table 1). Confidence scores for these photos were as follows: High (n = 19), Probable (n = 48), and Moderate (n = 19); all were included in the analysis since even the lowest confidence score still represents over 50% confidence of the scar originating from an entanglement injury.

Discussion

Entanglement Scar Acquisition Rate

The estimated acquisition rate (2.2%/yr) suggests that the probability of acquiring a scar over the 25 yr study is approximately 43%. Although this might seem high, a look at the raw data confirms this finding: of the 68 whales in the data set, 13 recaptures had elapsed times of at least 25 yr, five whales (38%) of which had acquired a scar (Tables 2, 3). George *et al.* (2017) found that about 50% of large harvested whales (~17 m) carried entanglement scars. The whales used for the interyear comparisons tended to be larger scarred animals averaging 14.2 m in body length when recaptured. Our scar acquisition rate estimate therefore applies mainly to adult whales, based on an average length-at-maturity for both sexes whose range is approximately 12–13.7 m (Koski 1993, George *et al.* 2018). When estimated ages (Wetzel *et al.* 2017) were assigned to the scar data set for landed whales (George *et al.* 2017) we found that about 49% (11 of 33) of the whales over 50 yr old carried entanglement scars.

Our binomial model predicts that by age 50, 42% to 81% of whales should have acquired a scar, while approximately 49% of whales estimated to be over age 50 are actually scarred. The fact that the latter percentage is on the low end of what might be expected from our model may be due to several artificial reasons including (1) sampling variation in the estimates of p, whale age, and/or scar prevalence, and (2) the fact that the scar acquisition data set is biased toward older animals since these are more likely to be marked and hence captured and recaptured in the photo-ID study. However, there is also potential biological significance to this finding. Examinations of harvested whales indicated that relatively few whales less than about 25 yr of age (~13.5 m) show scarring (George *et al.* 2017). Neilson *et al.* (2009) provide evidence from humpback whales that the younger age classes have higher mortality rates from entanglement. If whales under 25 yr of age are more likely to die from entanglement, then the 2.2% annual rate of scarring might apply mainly to larger mature whales (since for bowheads, maturity corresponds roughly to ~13.5 m or about 25 yr).

For the maximum likelihood binomial approach to estimating scar acquisition rate, there were several whales that were recaptured more than once. In these cases, we considered each interval between captures to be a separate trial. Although the independence assumption may not be entirely valid in these cases, *e.g.*, some individuals may have habitat preferences that overlap more with fishing activities putting them at higher risk of entanglement, we believe that strong dependence is unlikely and the effect would be small, especially since such cases represent only a small portion of the entire data set.

It is worthwhile to consider the relative merits of the survival analysis and binomial approaches. Generally, we prefer the survival analysis for two reasons. First, it is nonparametric, requiring no assumed model and no particular shape of the "survival function," *i.e.*, the functional relationship between time of exposure and probability of scar acquisition, aside from monotonicity. The survival method also does not require the type of independence assumption used by the binomial approach. Second, the survival analysis makes full use of the information in the data because it explicitly recognizes left and right censoring. For example, in a right censored observation, the binomial model uses the information that "the whale did not acquire a scar in the previous period," whereas the survival model uses the information that "the whale did not acquire a scar *for at least as long as* the previous period, and maybe longer." Notwithstanding these points, it is reassuring that both statistical models produce similar results.

There are several other points to note when considering these results: (1) our data set is a sample of whales with distinctive scarring matched during the photo-ID project; it is not clear whether these are representative of all whales, with respect to scar acquisition rate. As noted earlier, marked-matched whales are more likely to be larger, older whales, while smaller (presumably younger) unmarked whales are less likely to be represented in this data set; (2) it is possible that the larger whales in our sample may spend the winter in regions of greater crab pot or fishery activity. That is, the wintering areas used by BCBS bowheads are still not well understood, but telemetry data strongly suggest bowheads' winter within the sea ice (Citta *et al.* 2012); (3) small or young whales (calves, yearlings, subadults) may be more likely to die from entanglement than adults (Robbins 2012). George *et al.* (2017) suggested exposure time to pot gear best explained the lack of entangled subadults in the harvest. Either way, an increasingly plausible explanation for the rarity of subadult whales with entanglement injuries in the harvest is that they have a higher mortality rate when entangled.

We recorded our degree of confidence in assigning an entanglement score to individual whales as described above. These scores were not used in the entanglement acquisition rate. This raises an important issue: the use of only "Probable" or better scars may introduce a positive bias in the scar rate estimate. If we use only scars scored as "High" confidence, the acquisition rate would be much lower. However, as noted earlier, our "Probable" score actually reflects reasonably good confidence (70%–90%) that the scarring on the peduncle is an entanglement injury. We repeated both scar acquisition analyses after treating "Moderate" confidence as if the whale was not scarred. This resulted in adding four additional whales: previously the whale had been called scarred in both photos (and hence excluded from the analysis), whereas now the whale was called unscarred (previously "Moderate") in the first photo and scarred in the second. Two whales had previously been called unscarred in the first photo and "Moderate" (and thus called scarred) in the second photo, but now the second photo was called unscarred. Thus the revised data set comprised 72 whales, of which 16 were scarred in the last image. Using this data set with the binomial model, the estimated annual scar acquisition rate was 2.5% with 95% confidence interval (1.3%, 3.6%). This is very close to the estimates from the original data set. The censored survival model also produced nearly the same fit as originally.

Neilson *et al.* (2009) reported that 8% of the adult humpbacks in Glacier Bay/Icy Strait had acquired new entanglement scars between 2003 and 2004, although sample size was small (n = 2 of 26). They also reported that calves were less likely to have entanglement scars than adults.

In an extensive multiyear analysis of NARWs, Robbins *et al.* (2015) estimated survival for various age classes of entangled and nonentangled whales. The survival rate for both sexes of initially entangled adults (0.731) is about 25% lower than nonentangled females (0.961) and males (0.986), and again increased (0.952) for whales that survived the first year of entanglement. The mortality rate of BCBS bowheads from entanglement in commercial fishing gear is unknown, but the survival rate may also be lower for whales that have escaped previous entanglement (Robbins *et al.* 2015).

The 2.2% annual scarring rate for BCBS bowhead is nearly an order of magnitude lower than for NARW (25.9% annually); nevertheless, this suggests entanglement is a significant issue whereby several hundred bowheads may become entangled and escape pot gear annually, resulting in sublethal impacts (van der Hoop *et al.* 2017). In addition, some whales, especially juveniles, may be drowning *in situ*.

Proportion of Whales with Entanglement Injuries 2011

As noted earlier, this study focused on scars to the peduncle, which is the most common region of entanglement scarring in large cetaceans and more easily observed than the pectoral fins and mouth in our aerial photos (*e.g.*, Fig. 1; Neilson *et al.* 2009, Robbins 2012). Unlike scarring associated with sea ice injuries, which are typically found on the dorsal surface of the head, thorax, and flukes, entanglement injuries on landed bowheads have primarily been observed on the caudal peduncle (Philo *et al.* 1993, George *et al.* 2017). Relatively few harvested bowheads have shown obvious entanglement scars to the mouth and pectoral fins. For NARWs, entanglement scars commonly occur elsewhere on the animal besides the peduncle. It is curious why scars to the mouth are seldom observed or recorded on harvested bowheads. It is possible that subtle scars to the mouth (on harvested whales) are missed and not recorded, bowheads feed less in winter when they are in regions where commercial fishing occurs and are, therefore, less susceptible to mouth-entanglement, or whales entangled through the mouth have a higher mortality rate.

We found remarkable agreement between our aerial photographic analysis and results from harvested bowheads (1990–2012). Among the landed whales (n = 485), 12.2% showed evidence of entanglement scarring (George *et al.* 2017), compared to 12.4% in our photographic analysis of live whales. This close agreement increases our confidence that the bowhead aerial photographic database is useful for identifying entanglement scarring.

General Thoughts

Over the past 30 yr, we have advanced our understanding of fishing gear entanglement of BCBS bowhead whales, yet there are still many unknowns, particularly about future fishing trends in US and Russia. With reduced winter sea ice cover, it is possible that the Bering Sea pot fisheries could move further north into bowhead wintering areas (Citta *et al.* 2012, 2013). However, based on past ship surveys and satellite telemetry, it appears that most tagged bowheads winter within the marginal and heavy pack ice zones (Citta *et al.* 2013), so the bowhead's wintering areas may also retreat north away from active fisheries. The bowhead's affinity for sea ice in winter is not necessarily the case in summer, when they are often found in open waters far from the ice.

On the other hand, some bowheads have been harvested at St. Lawrence Island south of the main pack ice in winter/spring, and historically many bowheads summered in the Bering Sea (1850s) where they are nearly absent now (Bockstoce *et al.* 2005); however, bowheads could reoccupy these areas as their abundance increases. Therefore, it is difficult to speculate on the environmental, economic, and biological effects, as well as future fishing effort in U.S. and Russian waters, on entanglement rates of BCBS bowheads in the future. As noted earlier, George *et al.* (2017) analyzed entanglement frequencies of harvested whales (1990–2012) for trends, but they were not statistically significant. The mark-recapture data set analyzed here, unfortunately, was insufficient for a temporal analysis (Table 3).

While outside the objectives of this study, postmortem examinations of harvested bowheads suggest that in cases where heavy line (19 mm) was wrapped on a whale, it caused injuries that greatly compromised the animal's health, and in some strandings was the likely cause of death (George *et al.* 2017). For NARWs, Knowlton *et al.* (2012) reported that severe entanglement injuries may result in reduced reproduction and increased susceptibility to disease. Furthermore, van der Hoop *et al.* (2017) reported drag from sublethal entanglement events in NARWs adds energetic costs that in reproductive females can delay reproduction for months to years depending on the duration of the entanglement and other factors. Similar reductions in fecundity may occur for some entangled female bowheads; however, calving rates for BCBS bowheads in recent years have been near historic highs (Clarke *et al.* 2018).

The Alaska Bering Sea/Aleutian Island crab pot fishery is classified as a Type III Fishery, defined as "remote likelihood or no known interactions" with marine mammals. In fact, table 1 of the NOAA 2017 List of Fisheries (LOF) includes only Eastern North Pacific gray whales (*Eschrichtius robustus*) under "Marine species and stocks incidentally killed or injured," with no mention of bowhead whales; however, several fatal and severe entanglements involving bowhead whales associated with Bering Sea crab gear have been reported[3,4] (George *et al.* 2017). It is unknown if active fishing gear or "ghost" gear, which has been lost or abandoned, is responsible. Rationalization of the crab fishery started in 2005[5] and led to a

[3]Sheffield, G., and SWCA (Savoonga Whaling Captains Association). 2015. Bowhead whale entangled in commercial crab pot gear recovered near Saint Lawrence Island, Bering Strait. University of Alaska Fairbanks, Alaska Sea Grant, Marine Advisory Program (Nome), Report to the North Slope Borough Department of Wildlife Management, PO Box 69, Barrow, Alaska 99723.

[4]Sheffield, G., 2010. A bowhead whale entangled in Bering Sea commercial pot gear, Chukchi Sea. Alaska Department of Fish and Game–Nome, Report to the North Slope Borough Department of Wildlife Management, PO Box 69, Barrow, Alaska 99723.

[5]Fisheries of the Exclusive Economic Zone Off Alaska; Allocating Bering Sea and Aleutian Islands King and Tanner Crab Fishery Resources. 50 C.F.R. 679 (2005).

significant reduction in the size of the Bering Sea crab fleet and number of pots deployed. This reduction in effort could lead to a decrease in the number of entangled bowheads—unless entanglement is primarily caused by lost and abandoned gear. It is also possible that some portion of the entanglement injuries occurred decades ago during the period of intensive crabbing. The Alaska Eskimo Whaling Commission (AEWC) and the Bering Sea Crabbers have met on three occasions (2016, 2017, and 2018), have discussed the issues, and agreed to work towards solutions.

Concluding Remarks

The BCBS stock of bowheads appears to be abundant, healthy, and has a relatively high rate of population increase in the face of sea ice-reduction, gear entanglement, and other threats (IWC 2018). This suggests that bycatch has not significantly interfered with the recovery of this stock from Yankee commercial whaling; furthermore, the rate of entanglement scar acquisition (2.2%/yr) is lower for BCBS bowheads than some other North Atlantic and Pacific large whale stocks. Nevertheless, the IWC, NOAA, and AEWC management and conservation goals are to maintain the robust status of this stock. It is clear from these data that entanglement in fishing gear is a nonignorable concern for BCBS bowheads. With a warming climate and more accessible arctic waters, commercial fishing and crabbing activity are expected to increase within the bowhead's range, and possibly within summering areas (Reeves *et al.* 2012). Without careful fisheries management, entanglements may increase. We strongly recommend that monitoring of the BCBS bowhead population for anthropogenic impacts should continue and steps should be taken now to minimize interactions and reduce the number of entanglements.

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