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SPECIAL ISSUE

Non-lethal entanglement of humpback whales (*Megaptera novaeangliae*) in fishing gear in northern Southeast Alaska

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ABSTRACT

Aim Entanglement in fishing gear is recognized as a potentially significant source of serious injury and mortality for humpback whales (*Megaptera novaeangliae*) in some parts of their range. In recent years, the number of humpback whales reported to have been entangled in Alaska has increased. In 2003–04 we quantified the prevalence of non-lethal entanglements of humpback whales in northern Southeast Alaska (SEAK) with the ultimate goal of informing management discussions of the entanglement issue for the Central North Pacific stock of humpback whales.

Location The near-shore waters of northern Southeast Alaska.

Methods We photographed individual humpback whales' caudal peduncles as they dived and then examined the photographs for scars indicative of a previous entanglement.

Results The percentage of whales assessed to have been non-lethally entangled at some time in their lives ranged from 52% (minimal estimate) to 71% (conditional estimate) to 78% (maximal estimate). Of these, the conditional estimate is recommended because it is based solely on unambiguous scars. Eight per cent of the whales in one portion of the study area (Glacier Bay/Icy Strait) acquired new entanglement scars between 2003 and 2004, although the sample size was small. Calves were less likely than older whales to have entanglement scars, and males may be at higher risk than females. Whales with more photographs and/or photographic coverage may be more likely to be assessed as having been entangled than whales with fewer photographs and/or coverage.

Main conclusions Caudal peduncle scars reveal that the majority of humpback whales in northern SEAK have been entangled. Comparison with statistics on reported entanglements suggests that most whales apparently shed the gear on their own, unless humans are disentangling whales much more often than is reported. While cumulative estimates of the percentage of whales with entanglement scars (e.g. the conditional estimate) provide useful baseline information, future efforts should focus on monitoring the annual rate of entanglement scar acquisition as a more powerful measure of contemporary entanglement rates. Our findings indicate that entanglement of humpback whales in fishing gear in SEAK is a management issue warranting increased attention. A proactive approach is needed to address the problem and to identify and implement preventive measures.

Keywords

Bycatch, endangered species, entanglement, fisheries, humpback whale, management, *Megaptera novaeangliae,* monitoring, Southeast Alaska.

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INTRODUCTION

Entanglement of marine mammals in fishing gear has been documented widely, and may affect significant proportions of some baleen whale populations (Kraus, 1990; Lien, 1994; Volgenau *et al.*, 1995; Knowlton & Kraus, 2001; Robbins & Mattila, 2001, 2004; Knowlton *et al.*, 2005). In recent years, the number of humpback whales (*Megaptera novaeangliae*) reported to have been entangled in Alaska has increased (National Oceanic and Atmospheric Administration (NOAA) Fisheries Alaska Regional Office, Juneau, AK, USA, unpublished data). This study constitutes the first systematic effort to quantify the problem.

Humpback whales in the Central North Pacific (CNP) stock winter mainly in the Hawaiian Islands and migrate in the summer to northern British Columbia and Alaska, west to Unimak Pass (Baker *et al.*, 1990; Perry *et al.*, 1990; Calambokidis *et al.*, 1997, 2001). Like all humpback whale stocks in US waters, this stock is listed as endangered under the US Endangered Species Act and as depleted under the US Marine Mammal Protection Act (MMPA). Within Alaska, seasonal aggregations of feeding humpback whales from the CNP stock form in several areas, including the near-shore waters of Southeast Alaska (SEAK), Prince William Sound, Kodiak and the Shumagin Islands (Baker *et al.*, 1986; Calambokidis *et al.*, 1997, 2001; Waite *et al.*, 1999; Witteveen *et al.*, 2004). These aggregations are relatively isolated, with minimal interchange documented among feeding areas (Baker *et al.*, 1986; Waite *et al.*, 1999; Calambokidis *et al.*, 1997, 2001; Witteveen *et al.*, 2004). In SEAK, the most recent population estimate was based on photo-identification data and yielded an estimate of 961 (95% confidence interval (CI): 657, 1076) individuals in 2000 (Straley *et al.*, in press). This is considered a minimum population estimate for SEAK because no data were collected in southern SEAK (Straley *et al.*, in press).

When an entangled humpback whale is reported, NOAA Fisheries records the type of gear involved based on observations made by the reporting party. Of the 52 humpbacks reported as entangled in Alaska between 1997 and 2004, the most common gear type was pot gear (46%), followed by unidentified line (23%) and gillnet (8%) (NOAA Fisheries Alaska Regional Office, unpublished data). In nearly half (48%) of all reports, whales collided with gear that appears to have originated in Alaska and/or British Columbia: crab pot, shrimp pot, unidentified pot, sport halibut hook and line. [From the late 1970s to 1999, a limited-entry (15 permits) pot fishery targeting spiny lobster (*Panulirus marginatus*) and slipper lobster (*Scyllarides squammosus*) existed in the northwestern Hawaiian Islands, but this fishery has been closed since 2000; 50 CFR (Code of Federal Regulations) 660.] The other gear types reported (longline, purse seine, gillnet, various other lines and nets) are used broadly throughout the annual range of humpback whales, so it is not always possible to pinpoint the geographical origin of these entanglements. Humpback whales sighted around the Hawaiian Islands in winter have been reported entangled in fishing gear originating from fisheries in Hawaii and Alaska (Mazzuca *et al.*, 1998; NOAA Fisheries Pacific Islands Regional Office, unpublished data), and throughout their annual range, humpback whales encounter miscellaneous synthetic marine debris of wide geographical origin.

The reliability of gear reports depends on the expertise of the observer and how closely they could examine the gear. Distinguishing between commercial, sport and subsistence fishing gear is often difficult unless surface buoys are marked with information identifying the owner, or the gear is of a variety used only commercially (e.g. purse seine). Despite many shortcomings in the gear data, it appears that the fishing gear types most often implicated in entanglements in Alaska (pot gear and gillnets) match the general gear types most often implicated in the western North Atlantic, where 41% of entangled humpbacks ($n = 22$) were entangled in pot gear and 50% were entangled in gillnets (Johnson *et al.*, 2005; cf. Lien, 1994).

Under the 1994 amendments to the MMPA [16 USC (US Code) 1361 *et seq.*], NOAA Fisheries annually categorizes US commercial fisheries based on the level of serious injury and mortality of marine mammals caused by each fishery. Category I fisheries are those in which the amount of annual serious injury and mortality of a marine mammal stock is ≥ 50% of the potential biological removal (PBR), which is the maximum number of animals (not including natural mortalities) that may be removed annually from a marine mammal stock while still allowing the stock to reach or maintain its optimum sustainable population size; category II fisheries are those in which the amount of annual serious injury and mortality is > 1% and < 50% of PBR; category III fisheries are those in which the amount of annual serious injury and mortality is ≤ 1% of PBR.

Within the typical annual range of SEAK humpback whales, the only fisheries classified as category I are some of the longline/set line fisheries in Hawaii, primarily due to interactions with false killer whales (*Pseudorca crassidens*), and only two fisheries are classified as category II (the SEAK salmon drift gillnet fishery and the SEAK salmon purse seine fishery), based on the cumulative serious injury and mortality of multiple marine mammal stocks, including humpback whales. All other commercial fisheries in SEAK and Hawaii with which SEAK humpback whales are likely to interact, including all pot fisheries, are classified as category III.

From a management perspective, an accurate measure of the serious injury and mortality rate due to fisheries interactions is clearly needed, but is difficult to obtain. Not all entangled whales are found or reported, and those that are reported are difficult to assess due to a lack of information accompanying most reports and a poor understanding of what makes entanglements fatal. For humpback whales in SEAK, the remoteness of the Alaska and northern British Columbia coastline, and the rarity with which humpback whale carcasses are found and reported (NOAA Fisheries Alaska Regional Office, unpublished data) make it difficult to examine dead humpback whales for evidence of lethal fisheries interactions.

Alternatively, if every live entangled whale or piece of lost fishing gear was found and tracked, then accurately calculating the rate of lethal entanglements might be possible, but the cost and effort required to undertake this level of monitoring are prohibitive.

In the absence of more comprehensive data, reports of live entangled whales provide much of the information that managers use to gauge the level of serious injury and mortality incidental to commercial fisheries in SEAK. However, because not all entangled whales are found or reported, an alternative approach to assessing the magnitude of fisheries interactions in a stock is to examine living whales for evidence that they have been entangled previously. This approach was pioneered in the western North Atlantic, where researchers studying northern right (*Eubalaena glacialis*) and humpback whales noted that wounds resulting from entanglements may remain visible as distinct scars (e.g. wrapping and binding scars, linear notches and other tissue damage) long after the entanglement event (Kraus, 1990; Robbins & Mattila, 1999, 2001, 2004; Knowlton & Kraus, 2001; Knowlton *et al.*, 2005). Photographic studies of entanglement scars offer the opportunity to sample a large number of animals in order to make inferences about the frequency of non-lethal entanglements in a population on a cumulative and annual scale.

In the western North Atlantic, the majority (53%) of entangled humpback whales (n = 30) had gear attached at the posterior caudal peduncle (the narrowing of the body at the insertion point of the flukes) (Johnson *et al.*, 2005). Entanglements involving the caudal peduncle are also common in grey whales (*Eschrichtius robustus*) (Heyning & Lewis, 1990) and northern right whales (Kraus, 1990). Humpback whales often raise their tail as they dive, making the caudal peduncle a relatively easy part of the body to photograph consistently and then examine for entanglement scars (Robbins & Mattila, 1999, 2001, 2004). In the Gulf of Maine, 48–65% of the humpback whales photographed annually between 1997 and 2002 had caudal peduncle scars that appeared to be entanglement-related, and tissue damage was evident (Robbins & Mattila, 1999, 2001, 2004). A comparison of scars on the same individuals between years revealed that 8–25% were entangled annually (Robbins & Mattila, 2004). Using a similar scar-based approach, Kraus (1990) concluded that 57% of North Atlantic right whales bear caudal peduncle entanglement scars.

In Hawaii, 14% of the humpback whales photographed in 2002 had caudal peduncle scars that appeared to be entanglement-related, and tissue damage was evident (Robbins & Mattila, 2004). The authors concluded that entanglement might be more prevalent among Gulf of Maine humpback whales than among those that migrated to Hawaii, but other interpretations were also possible. Entanglement scar studies performed on North Pacific feeding grounds linked to Hawaii could therefore help to clarify this result.

The objectives of this study were: (1) to analyse caudal peduncle scars on humpback whales in northern SEAK to estimate the percentage of animals that have been non-lethally entangled, and (2) to analyse the scar data in conjunction with demographic data to identify any particularly vulnerable segments of the population.

METHODS

Study area

The main study area encompassed the near-shore waters of northern SEAK, approximately 57–59° N (Fig. 1). The primary survey areas were Glacier Bay, Icy Strait and Frederick Sound. In addition, we surveyed lower Lynn Canal, Chatham Strait, Seymour Canal, Peril Strait and Sitka Sound.

Whale surveys and data collection

We collected data in Glacier Bay and Icy Strait *c.* 4–5 days per week from 1 June to 31 August in 2003 and 2004, and 1–2 days per week in May, September, October and November 2003 and 2004. We surveyed other parts of northern SEAK intermittently, most of the effort occurring during two 10-day surveys in August 2003 and August 2004.

We approached and photographed humpback whales from outboard-driven motorboats 4–6.5 m long, using single lens reflex cameras equipped with 300- or 70–210-mm lenses. In 2003, the majority of photographs were taken with a 35-mm Nikon N90 camera using Kodak TMAX 3200 black-and-white print film shot at 1600 ISO, but some colour images were also taken with a 6.1-megapixel Nikon D100 digital camera in RAW file format shot at 400 ISO. In 2004, all images were collected digitally. Photographs were taken of each whale's caudal peduncle by operating the boat parallel to and slightly forward of each whale as it dived. When conditions allowed, we photographed both the left and right side of the caudal peduncle. To avoid bias towards scarred whales, we took caudal peduncle photographs of all suitably positioned whales, regardless of whether any entanglement scars were visible. We also took photographs of the pigmentation and morphology of the ventral surface of the flukes and dorsal fin for individual identification (Jurasz & Palmer, 1981; Katona & Whitehead, 1981; Blackmer *et al.*, 2000). We used data sheets to record the date and latitude/longitude (determined with a global positioning system) where we encountered each whale.

Photographic data analysis

We identified each whale by matching its flukes and/or dorsal fin photograph(s) to photographs of individual humpback whales previously identified in the CNP, then grouped the photographs by year and individual whale. We converted the film to digital images using a 35-mm negative film scanner (Nikon Coolscan 4000ED with NIKON SCAN ver. 3.1.2 software; Nikon, Melville, NY, USA), then conducted scar analysis as described and ground-truthed against documented entanglements by Robbins & Mattila (1999, 2001, 2004). We divided each whale's caudal peduncle into six coding areas (dorsal peduncle, ventral peduncle, right

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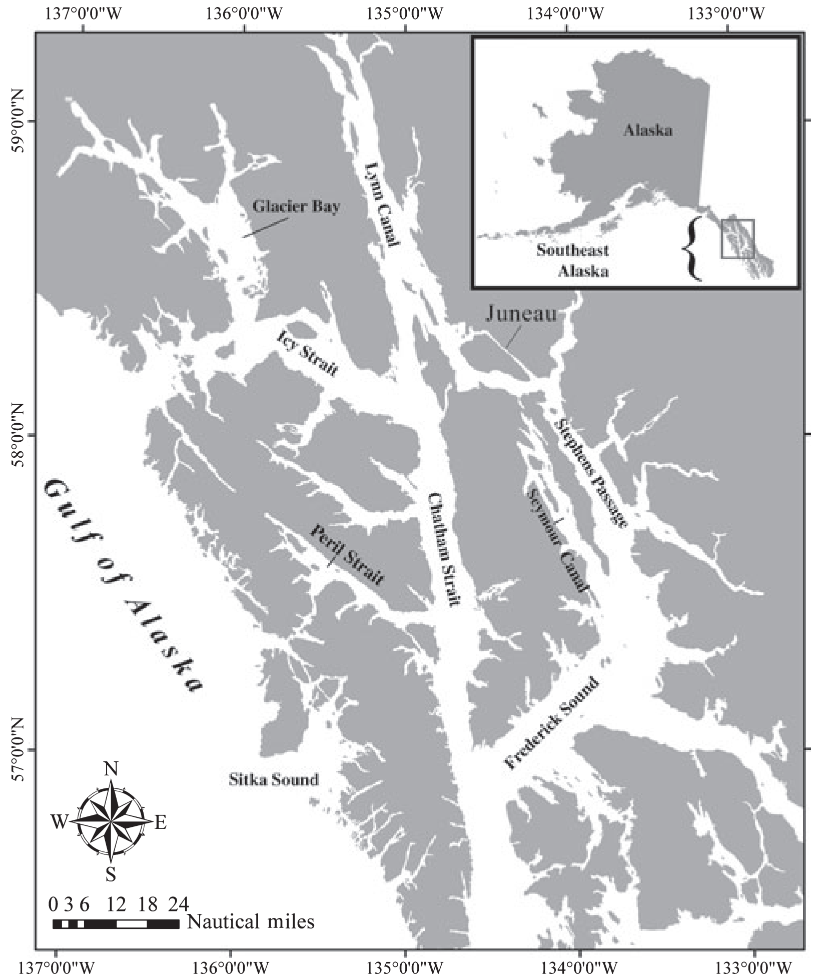

Figure 1 Study area in northern Southeast Alaska.

leading edge of flukes, left leading edge of flukes, left lateral peduncle, right lateral peduncle) (Fig. 2) and then assigned a scar code (Table 1) to each area based on the presence/absence of entanglement-related scarring. The six scar codes culminated in an overall entanglement status code (Table 2; Fig. 3). All codes were assigned by one person (J.L.N.) with input and review by another experienced coder (Jooke Robbins, Provincetown Center for Coastal Studies, Provincetown, MA, USA) to ensure coding was consistent with that conducted in previous studies in the Gulf of Maine and Hawaii (Neilson, 2007). Some entanglement scars are obvious even in very poor photographs, but to avoid biasing the analysis towards scarred whales, we assigned entanglement status codes 'low', 'ambiguous' and 'high' only to whales with adequate photographic coverage in at least two of the six caudal peduncle coding areas. Thus we assigned the code 'unknown' to whales without this coverage, despite clear signs that they had been entangled previously.

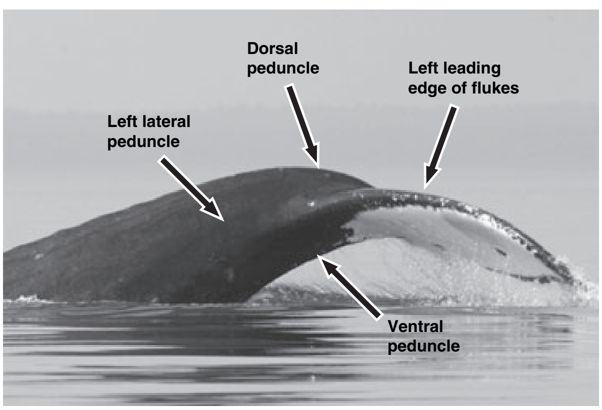

Figure 2 Sample caudal peduncle photograph illustrating four of the six areas used in coding (after Robbins & Mattila, 2001).

Percentage of whales with non-lethal caudal peduncle entanglement scars

Three methods were used to estimate the percentage of whales with non-lethal entanglement scars:

$$\text{minimal scarring percentage} = \sum_{\text{HIGH}} \Big/ \left(\sum_{\text{LOW}} + \sum_{\text{AMBIGUOUS}} + \sum_{\text{HIGH}}\right)$$

Table 1 Summary of scar codes (after Robbins & Mattila, 2001) – each whale's caudal peduncle was divided into six areas and assigned a scar code.

Scar code	Description
S0	No visible marks
S1	Non-linear or apparently randomly oriented linear marks
S2	Linear marks or wide areas lacking pigmentation, which did not appear to wrap around the feature
S3	Linear or wide scars, which appeared to wrap around the feature
S4	At least one visible linear notch or indentation (generally on dorsal or ventral peduncle)
S5	Extensive tissue damage and deformation of the feature
SX	Feature could not be coded due to lack of photographic coverage or inadequate photo quality

Table 2 Summary of entanglement status codes (after Robbins & Mattila, 2001) – the six scar codes culminated in an overall entanglement status code for each whale.

Entanglement status code	Description
Low	No marks observed, or marks were observed but did not suggest a previous entanglement. Scar codes did not generally exceed S2 in any documented region
Ambiguous	Entanglement-like elements were present, but there was no consistent pattern. At least one region was generally assigned a scar code of S3 or higher
High	Marks appeared to be entanglement-related and tissue damage was evident. At least two regions were generally assigned scar codes of S3 or higher
Unknown	Whale could not be assigned an entanglement status code due to lack of photographic coverage or inadequate photo quality

conditional scarring percentage

$$= \sum_{\text{HIGH}} / \left(\sum_{\text{LOW}} + \sum_{\text{HIGH}}\right)$$

maximal scarring percentage

$$= \left(\sum_{\text{HIGH}} + \sum_{\text{AMBIGUOUS}}\right) / \left(\sum_{\text{LOW}} + \sum_{\text{AMBIGUOUS}} + \sum_{\text{HIGH}}\right)$$

where LOW, AMBIGUOUS, HIGH = number of whales assigned the entanglement status codes 'low', 'ambiguous' and 'high', respectively.

The minimal scarring percentage was used to estimate the percentage of previously entangled humpback whales in the Gulf of Maine and Hawaii (Robbins & Mattila, 2001, 2004). As they noted, this approach is likely to underestimate the true percentage of entangled whales, because some of the whales coded as ambiguous may have been entangled. The conditional scarring percentage is based solely on individuals with unambiguous caudal peduncle scars, but may be biased towards recent entanglements, and decreases the sample size because it omits whales coded as ambiguous. The maximal scarring percentage is likely to overestimate the true percentage of entangled whales because it is unlikely that all the whales coded as ambiguous were entangled.

When data from both years were pooled, whales that were seen both years were counted once. If there was a difference in a whale's coded status between years, the 2004 code was used (unless it was unknown, in which case the 2003 code was used).

Annual rate of entanglement scar acquisition

Following Robbins & Mattila (2004), we also compared individual whales' caudal peduncle images from 2003–04 to estimate the annual rate of entanglement scar acquisition

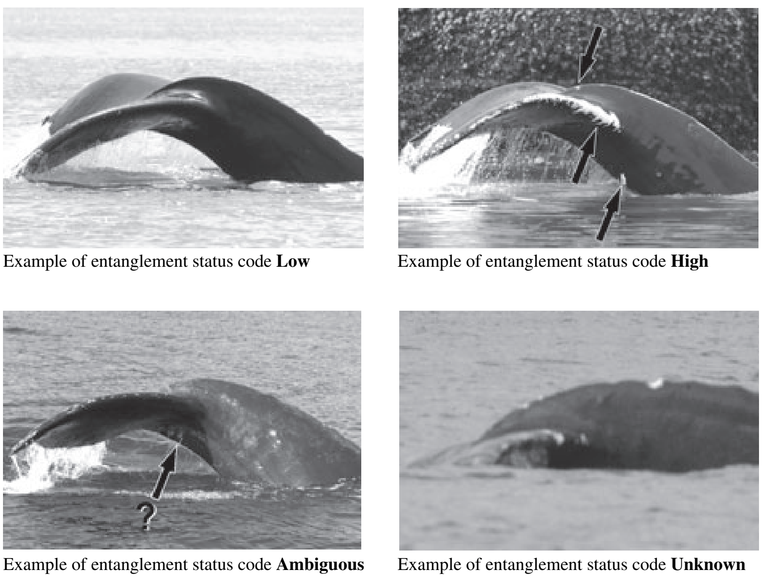

Figure 3 Illustrations of entanglement status codes. Arrows highlight key features and do not represent the total number of entanglement scars observed.

between 2003 and 2004. We divided the number of whales that acquired entanglement scarring by the total number of whales with adequate photographic coverage in both years.

Identification of vulnerable segments of the population

We obtained sex and birth year for individual whales previously identified in SEAK from data bases maintained by long-term humpback whale-monitoring programmes based at Glacier Bay National Park & Preserve (GBNPP) in Gustavus, AK, USA and at J. Straley Investigations and University of Alaska Southeast in Sitka, AK, USA. Sex was determined by genetic analysis of skin samples (Gilson *et al.*, 1998) and/or photographs of the genital slit (Glockner, 1983). In addition, any whale that was observed in close association with a calf on one or more occasions was considered to be a female. We defined calves as whales < 1 year old, and juveniles as whales > 1 year old but < 5 years old (Clapham, 1992).

Statistical analyses

We calculated 95% CI (Zar, 1999) on the scarring percentages and used Fisher's exact test (Zar, 1999) to test for significant differences between percentages. When comparing percentages, we estimated the power of each test according to Zar (1999).

RESULTS

Photographic data analysis

We collected caudal peduncle images of 152 and 224 unique whales in 2003 and 2004, respectively. Seventy-three whales were photographed in both years, resulting in 303 unique whales in the combined 2003–04 sample. We obtained adequate photographic coverage for 47% ($n = 72$) of the whales in the 2003 sample and for 61% ($n = 137$) of the whales in the 2004 sample (Table 3). In total, we determined the entanglement status of 180 unique individuals.

Percentage of whales with caudal peduncle entanglement scars

In 2004, a larger sample of whales than in 2003 allowed for greater precision in the scarring percentages (Table 4). The minimal, maximal and conditional scarring percentages in 2003 and 2004 were not significantly different between years ($P = 1$, two-tailed Fisher's exact tests for all comparisons), therefore the data from both years were pooled (Table 4).

Table 3 Entanglement status codes assigned to whales in 2003–04; numbers cannot be added directly because some whales were seen in both years.

Year	*n*	Low	Ambiguous	High	Unknown
2003	152	16	17	39	80
2004	224	31	33	73	87
2003 + 2004	303	39	47	94	123

Table 4 Entanglement scarring percentages for all whales, 2003–04 (95% CI).

Year	*n*	Minimal scarring (%)	Maximal scarring (%)	*n*	Conditional scarring (%)
2003	72	54 (42, 66)	78 (67, 87)	55	71 (57, 82)
2004	137	53 (45, 61)	77 (69, 84)	104	70 (60, 79)
2003 + 2004	180	52 (45, 60)	78 (72, 84)	133	71 (62, 78)

Variation in amount of photographic coverage

Using the minimal scarring percentage approach, whales with adequate photographic coverage of one side of the caudal peduncle were significantly less likely to be assessed as having been entangled than whales with adequate photographic coverage of both sides ($P = 0.035$, one-tailed Fisher's exact test; Table 5). When the maximal and conditional approaches were used, the differences in percentages between whales with coverage of one vs. both sides were not significant ($P = 0.273$, $P = 0.126$, one-tailed Fisher's exact test); however, the power to detect a difference in these comparisons was lower.

The mean number of photographs of whales coded as high (8.4 photographs per whale) was greater than the mean number of photographs of whales coded as low or ambiguous (5.8 photographs per whale) and the difference was significant (unpaired *t*-test, $t = 3.31$, d.f. = 178, $P = 0.001$).

Whales photographed in both years

Twenty-eight whales had adequate photographic coverage in both years; all were adults. None exhibited a decrease in entanglement scarring between years, 26 (93%) exhibited stable scars, and two (7%) exhibited an increase in entanglement scarring attributed to having been entangled. In two (2/28 = 7%) cases, inter-annual differences in photographic quality and/or the angle of the photographs led us to assign different entanglement status codes to the same whale between years, despite no changes in the amount of scarring. The effects of this variation on the minimal, maximal and conditional scarring percentages differ in each case.

Table 5 Entanglement scarring percentages of whales with adequate photographic coverage of one vs. both sides of the caudal peduncle for both years combined (95% CI).

No. sides	*n*	Minimal scarring (%)	Maximal scarring (%)	*n*	Conditional scarring (%)
One side	40	40 (25, 57)	75 (59, 87)	26	62 (41, 80)
Both sides	131	58 (49, 67)	81 (73, 87)	101	75 (66, 83)

Whale coded ambiguous in 2003 then high in 2004

No change in maximal scarring percentage. However, it raises both the minimal scarring percentage (by increasing the value of the numerator) and the conditional scarring percentage (by increasing the value of the numerator and lowering the value of the denominator.) The conditional estimate changes less than the minimal estimate, thus the conditional estimate is more robust than the minimal estimate to this type of change in coding.

Whale coded low in 2003 then ambiguous in 2004

No change in minimal scarring percentage. However, it raises both the maximal scarring percentage (by increasing the value of the numerator) and the conditional scarring percentage (by lowering the value of the denominator). The conditional estimate changes less than the maximal estimate, thus the conditional estimate is more robust than the maximal estimate to this type of change in coding.

Annual rate of entanglement scar acquisition

Twenty-six of the 28 whales that were documented in both years were sampled in Glacier Bay and Icy Strait, reflecting the concentration of survey effort in these locations. Limiting the sample to only these 26 whales to avoid potential area effects, two (8%) acquired caudal peduncle entanglement scars between years. One whale acquired entanglement scars that had previously had none; the other whale acquired new entanglement scars in addition to pre-existing ones.

Identification of vulnerable segments of the population

Sex

The minimal, maximal and conditional scarring percentages for males, females and whales of unknown sex were not significantly different between 2003 and 2004 ($P \geq 0.157$, two-tailed Fisher's exact tests); therefore data from both years were pooled (Table 6).

Males' minimal scarring percentage (82%) was higher than that of females (55%) and the difference was significant ($P = 0.013$, two-tailed Fisher's exact test). Males' and females' maximal scarring percentages (males 88%, females 79%) and conditional scarring percentages (males 87%, females 72%) were not significantly different ($P = 0.402$, $P = 0.165$, two-tailed Fisher's exact tests); however, the power to detect a difference in these comparisons was lower.

These results are influenced by males having a greater amount of caudal peduncle photographic coverage per whale (mean 1.9 sides) than females (mean 1.7 sides), and the difference was significant (unpaired *t*-test, $t = 2.64$, d.f. = 93, $P = 0.01$). Males had more caudal peduncle photographs per whale (mean 10.2) than females (mean 7.7), but the difference was not significant (unpaired *t*-test, $t = 1.77$, d.f. = 93, $P = 0.08$). The two whales in Glacier Bay/Icy Strait with an increase in entanglement scarring between years were males.

The percentage of females coded ambiguous (24%) was higher than the percentage of males coded ambiguous (6%), and the difference was significant ($P = 0.046$, two-tailed Fisher's exact test).

Table 6 Entanglement scarring percentages by sex for both years combined (95% CI).

Sex	*n*	Minimal scarring (%)	Maximal scarring (%)	*n*	Conditional scarring (%)
Male	33	82 (65, 93)	88 (72, 97)	31	87 (70, 96)
Female	62	55 (42, 68)	79 (67, 88)	47	72 (57, 84)
Unknown	85	39 (28, 50)	74 (63, 83)	55	60 (46, 73)

Age

The sample of juveniles from both years combined ($n = 3$) was too small to treat juveniles as a separate age class in statistical analyses so they were pooled with older whales; however, all three juveniles were coded high.

Older whales' minimal, maximal and conditional scarring percentages were not significantly different between 2003 and 2004 ($P = 1$, two-tailed Fisher's exact tests, for all comparisons), therefore data from both years were pooled (Table 7). For calves, data from both years were pooled (Table 7) to achieve sufficient sample sizes for statistical testing of differences in entanglement scarring percentages by age class.

Calves' minimal (17%) and conditional scarring percentages (29%) were lower than older whales' minimal (55%) and conditional scarring percentages (73%), and the differences were significant ($P = 0.015$, $P = 0.023$, two-tailed Fisher's exact tests). Calves' maximal scarring percentage (58%) was not significantly different from that of older whales (80%) ($P = 0.137$, two-tailed Fisher's exact test); however, the power to detect a difference in this comparison was lower.

Calves and older whales had the same amount of photographic coverage of the caudal peduncle per whale (mean 1.8 sides). Older whales had more caudal peduncle photographs per whale (mean 7.3) than calves (mean 6.5), but the difference was not significant (unpaired *t*-test, $t = 0.47$, d.f. = 166, $P = 0.64$).

The percentage of calves coded ambiguous (42%) was higher than the percentage of older whales coded ambiguous (25%), but the difference was not significant ($P = 0.304$, two-tailed Fisher's exact test).

Table 7 Entanglement scarring percentages by age class for both years combined (95% CI).

Age class	*n*	Minimal scarring (%)	Maximal scarring (%)	*n*	Conditional scarring (%)
Calves	12	17 (2, 48)	58 (28, 85)	7	29 (4, 71)
Older whales	168	55 (47, 62)	80 (73, 86)	126	73 (64, 81)

DISCUSSION

Percentage of whales with caudal peduncle entanglement scars

The entanglement scarring percentages revealed by this study (Table 4) indicate that the majority of humpback whales in northern SEAK have been non-lethally entangled at some time in their lives. Comparison with statistics on reported entanglements suggests that most whales apparently shed the gear on their own, unless humans are disentangling whales much more often than is reported. We believe that these results are representative of humpback whales in northern SEAK, given the broad geographical coverage of our sampling effort. However, a scar-based approach is expected to underestimate the true frequency of entanglement, because whales that were entangled once were coded the same as whales that had been entangled multiple times. In addition, our results indicate that whales with more photographs and/or photographic coverage may be more likely to be assessed as having been entangled, thus our method may underestimate the incidence of entanglement for whales with fewer photographs and/or less photographic coverage. Finally, a scar-based approach cannot account for: (1) whales that died before their scars could be detected, (2) entanglements that did not involve the caudal peduncle, and (3) entanglement injuries that had healed beyond recognition.

The minimal scarring percentages in northern SEAK in 2003 (54%) and 2004 (53%) (Table 4) are similar to the minimal scarring percentages documented in recent years for humpback whales in the Gulf of Maine (Robbins & Mattila, 1999, 2001, 2004), but higher than the minimal scarring percentage documented for humpback whales in Hawaii (Robbins & Mattila, 2004). At the time of that study, it was not known whether the lower result for Hawaii indicated: (1) a lower incidence of non-lethal entanglements in the CNP stock, (2) a higher incidence of lethal entanglements that could not be detected by scar analysis, and/or (3) an artefact of the sampling in Hawaii (e.g. a lower number of caudal peduncle photographs per whale). The present study demonstrates that the lower result for Hawaii was not due to a lower incidence of non-lethal entanglements in all CNP feeding areas. It seems likely that, in Hawaii, whales from northern SEAK mix with whales from other CNP feeding grounds with a lower incidence of non-lethal entanglements. Caudal peduncle photographs of humpback whales on feeding grounds across the North Pacific were collected in 2004–05 by researchers participating in the Structure of Populations, Levels of Abundance and Status of Humpbacks (SPLASH) programme, a North Pacific basin-wide humpback whale research programme. Analysis of these results is under way, and should allow a determination of whether entanglement scarring percentages are significantly different among various humpback whale summer feeding grounds in the North Pacific.

The proportion of ambiguously scarred whales in northern SEAK (24%) is comparable with that documented on average in the Gulf of Maine (28%; Robbins & Mattila, 2001). Whales with an ambiguous entanglement history are likely to represent animals with entanglement wounds that have partially healed, animals that have experienced less severe entanglements, and/or animals with wounds from other sources.

Minimal, conditional and maximal scarring percentages represent crude estimates of the cumulative incidence of non-lethal entanglements in a population and thus provide useful baseline information. Computer data simulations are needed to determine which approach produces the estimate that most closely represents the method's underlying assumptions and is thus the most accurate. However, based on the results of this study, we recommend the conditional scarring percentage (71%), which excludes whales with ambiguous scars. These whales' ambiguous entanglement histories (by definition) are a compelling reason to use the conditional approach. In addition, in this study the conditional scarring percentage was more robust than the minimal scarring percentage to variation in the amount of photographic coverage of the caudal peduncle (one side vs. both sides). The conditional scarring percentage was also more robust than the minimal scarring percentage to changes in a whale's entanglement status code from ambiguous to high. Finally, the conditional scarring percentage was more robust than the maximal scarring percentage to changes in a whale's entanglement status code from low to ambiguous. In studies with small sample sizes, the conditional approach may result in prohibitively small sample sizes (and thus wide confidence intervals), but that was not an issue in this study. It should be noted, however, that excluding whales with ambiguous scars may bias the conditional scarring estimate against older and less severe entanglement events. For example, some whales with known entanglement histories have been mistakenly coded as ambiguous (Robbins & Mattila, 1999).

Two (7%) of our assessments changed between 2003 and 2004 due to the inherently subjective nature of the scar-coding process, inter-annual differences in photographic quality, and slight variations in the lighting and angle of photographs. However, these types of change occurred at such a low rate that we do not believe they significantly biased our results. Similar low rates of inter-annual variability were found in the Gulf of Maine entanglement scar study (4%), where the authors concluded that in a small percentage of cases, some variability in coding is unavoidable (Robbins & Mattila, 2004).

Annual rate of entanglement scar acquisition

While the conditional scarring percentages provide useful baseline information, we agree with Robbins & Mattila (2004) that measuring the annual rate of entanglement scar acquisition is the most sensitive indicator of the magnitude of the entanglement problem, especially given the long-term stability of some caudal peduncle entanglement scars, the potential for others to heal beyond recognition, and the fact that whales may be entangled multiple times (GBNPP, unpublished data; Robbins & Mattila, 2001, 2004). Eight per cent of the whales in Glacier Bay and Icy Strait were estimated to have acquired new entanglement scars between 2003 and 2004, although this estimate is highly uncertain (95% CI: 1, 25%). Similar rates of annual entanglement scar acquisition were found in the Gulf of Maine from 1997 to 2002 (Robbins & Mattila, 2004).

By applying an 8% annual rate of entanglement scar acquisition to the best population estimate for the 2000 humpback whale population in Glacier Bay and Icy Strait (n = 169) (Straley *et al.*, in press), we estimate that between 2003 and 2004 about 12 or 13 (point estimate 12.5) of the whales in Glacier Bay and Icy Strait had non-lethal entanglements and self-released. However, between 2003 and 2004, only one humpback whale was reported entangled in Glacier Bay/Icy Strait. A second humpback was reported entangled, but may have been the same as the first (NOAA Fisheries Alaska Regional Office, unpublished data). Clearly, more whales are being entangled (and shedding the entangling gear without human intervention) in northern SEAK than are reported to NOAA Fisheries.

In the Gulf of Maine, only 3% of the humpback whales assessed to have been entangled between 1997 and 1999 were reported as entangled whales (Robbins & Mattila, 2001). Calculating the reporting rate hinges on photographically identifying the whales that are reported entangled so that their records can be linked with the entanglement scar data. The reporting rate in northern SEAK could not be calculated because only one of the 13 whales reported throughout the region in 2003–04 was identified. Increased efforts to photographically identify entangled whales in SEAK, combined with continued efforts to use caudal peduncle scarring to detect whales that have been entangled over a specific time period, are needed to generate an estimate of the reporting rate of entanglements in northern SEAK.

Identification of vulnerable segments of the population

Sex

Although the conditional scarring percentage is recommended, and resulted in no significant difference between male and female humpback whales in northern SEAK, the minimal scarring percentage indicates that males may be more likely than females to become non-lethally entangled (Table 6). It is unknown why male humpback whales in northern SEAK would have a higher minimal entanglement percentage than females. This appears to be related to the fact that a higher proportion of females than males had an ambiguous entanglement history (females 24%, males 6%). The scarring percentage estimates based on sex may also have been influenced by differences in the number of caudal peduncle photographs that were available for males and females. It is unknown why males had a greater amount of caudal peduncle photographic coverage than females. It was assumed that all whales had an equal chance of being photographed, but there may have been behavioural differences between males and females that made it easier to obtain photographs of both sides of males' caudal peduncles. For example, many females with calves were present in the study area in 2004, and it is possible that these females were less likely to tolerate close approaches by the survey vessel due to the presence of their calves.

Between 1997 and 1999 in the Gulf of Maine, significantly higher percentages of male than female humpback whales were found to have entanglement scarring (Robbins & Mattila, 2001). However, this pattern has not persisted over time, perhaps due to changes in the distribution of high-risk fishing gear and/or animal foraging patterns (Robbins & Mattila, 2004). Knowlton *et al.* (2005) found no significant differences by sex in the number of North Atlantic right whales with entanglement scars from 1980 to 2002.

It seems unlikely that our interpretation of caudal peduncle scars on male humpback whales was confounded by breeding ground injuries. Robbins & Mattila (2004) investigated this possibility and concluded that caudal peduncle scars from entanglement were distinctive enough that they were unlikely to be confused with breeding ground injuries. While a specific study of age–sex segregation of humpback whales in SEAK has not been conducted, there are no indications that male and female humpback whales select different habitats in SEAK (J. Straley Investigations, Sitka, AK, USA, unpublished data; GBNPP, unpublished data) where the distribution of fishing gear may pose different levels of risk. However, differences in the timing of migration between the sexes (Gabriele, 1992; Craig *et al.*, 2003) could potentially expose males to different opportunities for fishery interactions throughout their geographical range. Another possible explanation is that males may be more likely than females to investigate gear that they encounter (Harris & Knowlton, 2001). Male-biased mortality among non-human mammals has often been explained in terms of more risky behaviours by males compared with females, but generally these risky behaviours are associated with competition for females (Owens, 2002), making this an unlikely explanation for the difference in minimal scarring percentages that we observed.

The reason why more females than males were assessed to have an ambiguous entanglement history is also unclear. If whales coded as ambiguous represent whales with entanglement scars that have healed beyond recognition, then perhaps male humpback whales 'fight' entangling gear more intensely than females, which could produce more severe injuries that are less likely to heal into ambiguous patterns. Alternatively, if female humpback whales live longer, on average, than male humpback whales (a pattern documented in many mammalian species; Owens, 2002), the higher proportion of ambiguous marks on females could be explained by females having a greater chance than males of living long enough to have their entanglement scars heal beyond recognition. Average and maximum life expectancies in humpback whales are poorly understood (Clapham & Mead, 1999), making it difficult to determine if this is a contributing factor.

Age

The minimal and conditional scarring percentages suggest that non-lethal entanglement scarring is significantly less common in calves than in older whales (Table 7). A lower incidence of scarring in calves is expected because calves had less time to accumulate entanglement scars than adults. The minimal scarring percentage of calves in northern SEAK (17%) was higher than in the Gulf of Maine, where only 9% of calves were assessed to have been entangled (Robbins & Mattila, 2001), but this is not a significant difference. Continued sampling of calves in SEAK would elucidate if the scarring percentages found during this study are typical.

Juvenile humpback whales in the western north Atlantic (Lien, 1994; Robbins & Mattila, 2001), juvenile North Atlantic right whales (Knowlton *et al.*, 2005), juvenile grey whales (Heyning & Lewis, 1990) and juvenile northern fur seals (Fowler, 1985) appear to have significantly higher rates of entanglement than older animals. In this study, the sample of juveniles ($n = 3$) was too small to estimate the percentage of juveniles that had been entangled. It would be useful to sample more juveniles to determine if whales in this age class are at a higher risk of non-lethal entanglement than whales in other age classes.

It is thought that calves and juveniles have a higher mortality rate from entanglements than adult whales because: (1) they are growing, so gear is more likely to become embedded, which may lead to lethal infections and/or restricted circulation; and (2) calves and juveniles may not have the strength necessary to break free from entangling gear due to their smaller size (Knowlton *et al.*, 2005). If younger animals are more likely than older animals to die from entanglements, this could explain the lower rate of entanglement scarring in calves. Humpback whale calves off the Pacific coast of Colombia were significantly more likely to be found dead from entanglement than adults (Capella Alzueta *et al.*, 2001). Between 1979 and 1995, the estimated calf mortality rate in the CNP stock was 15–24%, but the causes of most of these mortalities are unknown (Gabriele *et al.*, 2001).

Management recommendations

We concur with Robbins & Mattila (2004) that measuring the annual rate of entanglement scar acquisition offers a systematic way to monitor entanglement trends in northern SEAK, therefore we recommend that future efforts focus on periodically measuring the percentage of whales that acquire new entanglement scars in two contiguous years. The annual rate of entanglement scar acquisition offers several advantages over cumulative estimates of scarring, including providing current trend data to managers, as well as being less prone to coding error (Robbins & Mattila, 2004). In the event that management initiatives are implemented with the aim of preventing entanglements (e.g. reducing the amount of gear in the water), the annual rate of entanglement scar acquisition might be an indicator of success; presumably the rate would decrease if prevention is effective. However, if management initiatives simply reduce the severity of entanglements (e.g. gear modifications such as weak links in fishing lines and/or nets), but not the number of entanglements, the annual rate of entanglement scar acquisition may not decrease (Knowlton *et al.*, 2005), because even entanglements that last for less than a day can produce diagnostic, persistent scarring (Robbins & Mattila, 2004). In fact, the annual rate of entanglement scar acquisition may even increase if whales that previously would have died from entanglements survive to be photographed, misleading managers into thinking that the measures implemented were not beneficial.

The results from this study indicate that the number of caudal peduncle photographs and the amount of photographic coverage collected per individual whale (Table 5) may influence the minimal, conditional and maximal entanglement scarring percentages. Because the minimal scarring percentage is sensitive to variation in the amount of photographic coverage of the caudal peduncle (one vs. both sides), if this approach is used, efforts should be made to obtain photographs of both sides of the caudal peduncle. More testing is needed to determine the minimum number of caudal peduncle photographs necessary to generate stable cumulative estimates of the percentage of whales with entanglement scars.

Overall, better photographic documentation of whale entanglements that are observed in SEAK is crucial because photographs may elucidate the type of material attached to the whale (e.g. net, rope, buoys), the body parts involved, the severity of the injuries, and the size and identity of the individual. These data are essential to learning how to prevent or mitigate the severity of entanglements. Photographs have also proven invaluable in evaluating the condition of entangled whales, deciding if they are candidates for disentanglement and planning how to attempt to remove the gear. This study would have benefited from having more historical photographs of entangled whales in SEAK, which would have allowed for ground-truthing of the scar-coding method for northern SEAK. Over the long term, a data set of photographically identified entangled whales and subsequent sightings of the same whales gear-free would allow managers to estimate minimum survival rates of entangled whales and to generate more specific determination criteria for what constitutes a serious injury under the MMPA.

Clearly, photographs taken during whale entanglements have the potential to yield important information, but their utility is limited. Photographs rarely reveal the type of fishing gear, or which part of the gear (e.g. groundline vs. surface buoy line) is entangled on the whale (Johnson *et al.*, 2005; NOAA Fisheries Alaska Regional Office, unpublished data). In the western North Atlantic, the type of entangling fishing gear was identified 80% of the time when entangled whales were observed by knowledgeable observers (e.g. fishermen, biologists) and/or when the entangling gear was recovered (Johnson *et al.*, 2005). Thus expanding the humpback whale stranding and disentanglement response network in Alaska has the potential greatly to increase the quantity and quality of data describing entanglements in this region, with the ultimate goal of informing initiatives aimed at prevention.

Our findings indicate that entanglement of humpback whales in fishing gear in SEAK is a management issue warranting increased attention. Fisheries interactions in northern SEAK appear to be occurring at a similar level to those in the Gulf of Maine, where disentanglement and preventive measures have garnered significant management attention. Before our study the magnitude of the problem was unclear, although increasing numbers of entanglement reports suggested that interactions of humpback whales with fishing gear were becoming more common. With an increasing humpback whale population (Straley *et al.*, in press), a proactive approach is needed to address this problem to prevent the potential biological removal being exceeded under the MMPA. Future work should focus on identifying the specific fisheries and locations that pose the greatest threats to humpback whales in SEAK, and working with sport and commercial fishermen to reduce entanglements. Increasing efforts to gather data from entangled whales in SEAK and throughout the Central North Pacific would improve our understanding of the issue and could lead to insights into potential preventive measures.

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