Scar-Based Inference Into Gulf of Maine Humpback Whale Entanglement: 2003-2006

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ABSTRACT

Entanglement in fishing gear is a known source of injury and mortality to humpback whales, *Megaptera novaeangliae*. However, eye-witnessed events provide limited insight into entanglement frequency, risk factors and biological impacts. The caudal peduncle is commonly implicated in humpback whale entanglements and is consistently presented during the terminal dive. Since 1997, peduncle scarring has been studied annually as a relative index of entanglement frequency among Gulf of Maine humpback whales. Between 2003-2006, a total of 2,155 suitable quality images were obtained of the caudal peduncle and flukes of 615 catalogued individuals. Preferred photographs were obtained while parallel to the whale and slightly ahead of its flukes during the terminal dive. Images were examined for evidence of wrapping scars, notches and other injuries that were believed to be entanglement-related. Nearly all (97.2%, n=35) individuals involved in eye-witnessed entanglements were independently scored as having a high probability of prior entanglement. The majority (64.9%, n=222) of individuals entering the study for the first time exhibited evidence of a prior entanglement. Unhealed high probability injuries were detected in the overall sample at annual frequencies ranging from 6.8 ± 3.59% (n=13, 2006) to 18.8 ± 4.16% (n=64, 2003). When baseline coverage was available, 35.8% (n=39) of new injuries occurred within one year, and 80.6% (n=87) to within 3 years. Inter-annual increases in scarring ranged from 6.3% (n=7, 2004) to 25.7% (n=27, 2003). There was significant annual variation during the study period, mainly related to a peak in adult entanglement between 2002 and 2003. There were no significant differences in entanglement incidence between the sexes, but juveniles were more likely than adults to acquire new injuries. A total of 156 new events were inferred from entanglement injuries during the study period. When reconciled with eye-witnessed cases, there were a total of 203 events

between 2003-2006. Only nine events were detected and well-documented in progress, resulting in a 5.7% reporting rate for the period. Annual humpback whale mortality from entanglement was estimated at approximately 3% (19-29 whales per year, depending on assumptions of population size). Mortality estimates were substantially greater than observed deaths, but not inconsistent with population vital rates. Entanglement mortality estimates also exceeded Potential Biological Removal (PBR) by a larger margin than observed deaths, reinforcing the importance of reducing the risk of entanglement.

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INTRODUCTION

The humpback whale (*Megaptera novaeangliae*) is a migratory cetacean that feeds at mid- to high latitudes and congregates at low latitudes to mate and calve. The Gulf of Maine is the southern-most humpback whale feeding stock in the North Atlantic. This region straddles U.S. and Canadian waters and humpback whales can be found there consistently from April through December. Animals aggregate at submerged banks and ledges, although they can be found in other areas and their spatial distribution varies with prey availability (Payne *et al.* 1990; Weinrich *et al.* 1997). In winter, the majority of the population is thought to migrate to the breeding range along the Atlantic margins of the Antilles, from Cuba to northern Venezuela (Winn *et al.* 1975; Balcomb and Nichols 1982; Whitehead and Moore 1982). However, a few Gulf of Maine whales remain in coastal U.S. waters in winter, whether in the Gulf of Maine itself (Robbins 2007) or off the U.S. mid-Atlantic states (Swingle et al. 1993). Nearly half of the humpback whales sampled in the latter area were from the Gulf of Maine, although whales from other feeding stocks were also represented (Barco et al. 2002).

North Atlantic humpback whales were historically subject to commercial exploitation (Mitchell and Reeves 1983; Smith and Reeves 2002). Like most humpback whale populations world-wide, those in the North Atlantic have been assumed to have increased by at least 50% since 1940 (IUCN 2008). However, specific efforts to assess recovery status in the North Atlantic were inconclusive (IWC 2002). In the U.S., the North Atlantic humpback whale is considered an endangered species that is vulnerable to human sources of injury and mortality, including fisheries by-catch (Anonymous 1991; Waring *et al.* 2007). However, the frequency of entanglement events, risk factors, and biological impacts remain poorly understood. The likelihood of witnessing an entanglement is thought to be low and variable, depending on entanglement location and overlap with knowledgeable observers. Between 2001-2005, there were 79 humpback whale entanglements witnessed along the U.S. East Coast, of which 70 were confirmed cases and 14 were either mortalities or considered likely to result in imminent death (Nelson et al. 2007). Confirmed entanglement sites of Gulf of Maine humpback whales range from Bay of Fundy, Canada to North Carolina (J.F. Kenney, pers. comm.). This number of observed deaths likely underestimates total entanglement mortality, which already exceeds what is considered sustainable for this population (Nelson et al. 2007).

Entanglements produce injuries that can be detected even after gear is removed or shed. Since 1997, scar analysis has provided additional information on the nature and frequency of entanglements on Gulf of Maine humpback whales (Robbins and Mattila 2000; 2001; 2004). This report describes the results of scar interpretation for the years 2003 through 2006. These data are also used to estimate entanglement reporting rates and the number of entanglement deaths in the Gulf of Maine population during that period.

METHODS

Witnessed entanglements

Data from documented entanglement events were obtained from the Atlantic Large Whale Disentanglement Network (ALWDN), coordinated by the Provincetown Center for Coastal Studies (PCCS, Massachusetts, USA) under the authority of the U.S. National Marine Fisheries Service (NMFS). PCCS has conducted disentanglements in the coastal waters of Massachusetts since 1984 and since 1997 the ALWDN has provided formal reporting, disentanglement response and awareness training along the eastern seaboard of the United States. The ALWDN attempts to obtain documentation of each entanglement, including the configuration of gear on the animal. Identifying features of the entangled whale are also obtained whenever possible so that the individual can be re-identified with or without entangling gear. We used this documentation to identify animals with confirmed entanglements, to study the injuries produced by entanglement and as a baseline for tracking the healing process. Observed events were also used to evaluate the effectiveness of eyewitness reporting (see below).

Free-ranging animals

Entanglements can involve any body part, but are typically anchored at the mouth, flippers and/or the tail (Johnson et al. 2005). On the U.S. East Coast, the tail was the observed anchoring site for at least 53% witnessed entanglements (Johnson et al. 2005), and raw injuries suggest that this figure under-estimates tail involvement. Unlike other attachment sites, the tail can be systematically sampled when it is raised above water each time the whale takes a terminal dive. We therefore used injuries and scarring in this area as an index of the entanglement history of the individual.

This study focussed on several body areas, including the posterior caudal peduncle, the insertion point of the flukes and their leading edges. Photographs were obtained in the Gulf of Maine, aboard PCCS research vessels conducting photo-identification (photo-ID) surveys and by PCCS naturalists aboard commercial whale watching vessels. Directed surveys targeted known humpback whale aggregation sites from Nantucket to Nova Scotia. Sampling effort was expended roughly proportional to observed whale density. In the case of commercial whale watching platforms, effort was restricted to the southwest Gulf of Maine, but humpback whales were the primary species of interest and an effort was made to photograph all animal approached. Images were generally obtained while alongside an animal and ahead of its flukes when it began its terminal dive. Photographers were instructed to photograph this part of the body whenever it was presented, without regard for injuries or scars observed in the field. Photographs were also taken when these features were exposed during rolling or lob tailing behaviors. The latter was particularly important for calves, which are less likely than older animals to systematically raise their tails upon diving. Images were obtained using digital SLR cameras equipped with a 300-mm telephoto or a 100-300mm zoom lens and shot in 24-bit color at a minimum resolution of 2160 x 1440 pixels.

Individual humpback whales can be identified from their natural markings, especially the ventral pigmentation of the flukes and the shape and size of the dorsal fin (Katona and Whitehead 1981). Identifying shots of each individual were matched to a photo-identification catalog of Gulf of Maine humpback whales maintained by PCCS since the 1970s. Sexes of Gulf of Maine humpback whales in this catalog were determined by genetic analysis of a tissue sample (Palsbøll *et al.* 1992; Bérubé and Palsbøll 1996a; b), a photograph of the genital slit (Glockner 1983) or, in the case of females, at least one documented calf. Age was known for individuals that were dependent calves at first encounter. Calves were classified in the field based on their physical size, stereotypical behaviors and close, consistent association with a mature female. They were assumed to range from 3 to 9 months old when first observed and typically remained dependent until at least October of their first year (Clapham and Mayo 1987; Baraff and Weinrich 1993). For animals without a known year of birth, a minimum age was assigned by assuming that the whale was at least 1 year old the first year it was sighted. Female humpback whales in the Gulf of Maine have been shown capable of producing a calf as early as age five (Clapham 1992), although the average age at first reproduction was closer to nine years during the study period (Robbins 2007). Animals first cataloged as calves and less than five years old in the year that they were sampled were considered juveniles. Whales were considered adults if they were known to be at least five years old or were first sampled as an independent whale at least four years prior to being sampled. An exact age could not be assigned to whales without a known year of birth and first cataloged less than four years prior to sampling. However, these were thought to be predominantly juvenile animals (Robbins 2007).

Entanglement scar analysis

A single individual (JR) examined evidence of a previous entanglement across six body areas: the right and left posterior flank, the right and left leading edge of the flukes, the dorsal peduncle and the ventral peduncle (Figure 1). High probability injuries consisted of healed scars or unhealed wounds that were consistent with wrapping around the feature (Figures 2 and 3). Healed injuries could be raised or indented and ranged from white to black in color when healed. We also made particular note of any injuries that did not appear to have healed, based on their color and texture. Unhealed injuries were gray, pink or red and had a different texture than healed injuries, with abrupt, angular edges and/or a roughened overall surface (Figures 2 and 3).

When multiple images were available from the same individual, we selected the best image per feature per day for analysis. Low quality photographs (based upon distance, angle and focus) were excluded from analysis to prevent a bias toward more obvious or severe injuries. Images taken of the right and left sides of the animal, when available, were initially evaluated independently. Data on documented entanglements and other known sources of injury were not factored into the initial coding process.

The first time that an individual was photographed, it was assigned to an entanglement history category based on its composite scar patterns. Animals with high probability scarring in at least two body areas were assigned a 'high' probability of a prior entanglement. Those with no diagnostic injuries or scars were considered to have a 'low' probability of prior entanglement. When injuries were detected in only one body area, entanglement was neither strongly supported nor ruled out. In those cases, the whale was assigned an 'uncertain' probability of previous entanglement. However, patterns of scarring in any given image represent a composite of events over the lifetime of the whale. Some injuries may have been acquired long ago, while others may have healed beyond recognition. Once we obtained at least one image of a feature, we focussed our attention on scarring or injuries that were not present in that baseline coverage. From one sampling period to the next, an individual's scarring pattern could remain the same, decrease as a result of healing or increase as new events occurred. Unhealed injuries were also flagged to better estimate the timing of injury acquisition and to identify recent events for whales without prior baseline images. New injuries were assumed not to have resulted from entanglement if they did not meet the above criteria for high probability of prior entanglement.

Entanglement frequency

Two approaches were used to estimate entanglement frequency over time. The first was the frequency of new high probability injuries among animals with comparable coverage in two consecutive years. However, some individuals were more likely than others to be re-sighted, others were not previously available for sampling (such as calves) and photographic coverage was not always exactly comparable when inter-annual re-sightings did occur. We therefore also calculated the frequency of unhealed, high probability injuries in each overall annual sample. Unhealed injuries were assumed to have been acquired within the previous year (see results) and therefore informative without a baseline sample. The results of these two approaches were later cross-referenced to produce a minimum count of entanglement events that likely occurred from one year to the next. The 95% confidence interval (*CI*) of percentages were calculated based on the standard error, as follows:

$$CI = 1.96\sqrt{\frac{p*(100-p)}{n}}$$

Where: p = the percentage of interest and n = total number of animals examined. Categorical differences between samples were evaluated using a G-test with a William's correction (Sokal and Rohlf 1981).

Comparison to documented events

Scar-based inference was evaluated using data from documented entanglement events. We calculated the frequency with which previously entangled individuals in our sample were successfully coded as having a high probability of entanglement. We also measured the persistence of unhealed entanglement injuries from the time that the gear was successfully shed or removed by disentanglement. The latter was done to better assess the value and limitations of unhealed injuries for tracking entanglements from one year to the next. Finally, we estimated the entanglement reporting rate for the study period by cross-referencing animals exhibiting new entanglement injuries in this study with those that were reported entangled during the same period. Scar-based cases that could not be linked to a documented event based on the identity of the individual and the timing of its injuries were considered unreported events.

Entanglement mortality

Free-ranging whales with entanglement injuries all lived beyond the entangling phase of their events. These cases can nevertheless provide insight into entanglement mortality if the ratio of entanglement survival to mortality can also be determined. We estimated the number of entanglement mortalities (*Nm*) during the study period based on the following formula:

$$Nm = ((Nt * E) / S) - (Nt * E)$$

Where: *Nt* = Total population size

E = Scar-based non-lethal entanglement rate

S = Percentage of non-lethal entanglements

Entanglement mortalities (*Nm*) were estimated for each year of the study period, using three different values for total population size. The first was the minimum population size most recently used by NMFS to calculate Potential Biological Removal (PBR) for this population (n=549, Waring *et al.* 2007). We also calculated a less conservative minimum estimate for Gulf of Maine humpback whales based on the "minimum number alive" in 2003 using data from PCCS longitudinal humpback whale research. The "minimum number alive" was the sum of the number of unique individuals sighted in the Gulf of Maine in the year 2003, plus those that were not seen in 2003, but documented both before and after that year. We selected the year 2003 because there was particularly high photo-identification effort in that year and this produced the highest annual value for the study period. Finally, we used the most recent NMFS abundance estimate for this stock, which was 847 individuals estimated from line-survey transects of the Gulf of Maine and part of the Scotian Shelf in 2006 (Waring *et al.* 2007). We used the point estimate of each annual scar-based non-lethal entanglement rate (*E*) as the best value for mortality estimates. However, we also calculated minimum and maximum mortality counts based on the 95% confidence limits of the entanglement rate. Data were also required on the fraction of entanglements that were non-lethal (*S*). For this, we used NMFS serious injury and mortality determinations, as these criteria are already used to determine when takes from eye-witnessed events exceed PBR (Glass *et al.* 2008). Of the confirmed entanglement cases between 2002-2006 with adequate documentation for assessment, 76.6% (n=49) were assessed as non-lethal while the remaining 23.4% (n=15) were considered serious injuries or mortalities (Glass *et al.* 2008, Tables 1 and 2). Given the sparse data available from observed events, this value was not calculated on an annual basis.

RESULTS

Sample composition

Between 2003-2006, a total of 2,155 caudal peduncle images were coded from 615 identified individuals (Table 1). Images were obtained through a combination of focal cruises and other PCCS research efforts. Not all images were considered to be of equal quality for determining entanglement status through blind coding techniques, but all were deemed potentially valuable for monitoring the same individual over time. Of the 377 unique adults sampled during the study period, only three were of unknown sex. The number of available photographs was slightly skewed toward females (56.8%, n=1159 images). This bias was likely due to the fact that a large percentage of the total sample (42.6%, 920 images) came from commercial whale watching platforms operating in the Stellwagen Bank region where females tend to be slightly more prevalent (Robbins 2007). Known and suspected juveniles (including dependent calves) made up 40.0% (n=254) of the total individuals sampled over the study period. They comprised approximately one-third of each annual sample, except in 2006 when they made up only 19.4% (n=37) of the individuals sampled. The majority of individuals entering the study for the first time were calves (19.2%, n=79) or other animals with sighting histories of four years or less (37.9%, n=156).

Entanglement injuries

Examples of unhealed injuries produced by documented entanglements during the study period are shown in Figure 2. These exhibited wrapping injuries and notches in at least two coding areas in all cases. When injuries across coding areas were tracked over time, those at the leading edges of the flukes were the most persistent, whereas injuries on the flanks of the caudal peduncle often healed without prominent white scarring and more difficult to detect later. Injuries to the ventral peduncle were least visible by the preferred angle of photographic approach. Thus, injuries at the leading edges and dorsal peduncle were most informative about prior entanglement by these techniques.

A total of 36 previously entangled humpback whales were sampled during routine scar-based monitoring. Prior entanglements occurred between 1985 and 2006 and all but one individual was classified as having a high probability of prior entanglement based on patterns of scarring. When re-sighting data were adequate to assess, the vast majority of documented entanglement injuries had healed within one year after the gear was removed or shed. Injuries that persisted in a partially unhealed state beyond one year tended to be associated with larger, more severe events.

Entanglement frequency

The majority (64.9%, n=222) of the individuals entering the study for the first time exhibited evidence of a prior entanglement. Of those, 18.0 % (n=40) exhibited unhealed injuries indicative of a recent event, likely within the previous year. The vast majority of the latter individuals were known juveniles or other individuals with short sighting histories. For individuals with prior baseline coverage, 35.8% (n=39) of new injuries occurred within one year and 80.6% (n=87) occurred within 3 years. The maximum bounded injury took place within 7.31 years of first detection. Inter-annual injury acquisition was lowest between 2003 and 2004 (6.3 ± 4.48%, n=7) and highest from 2002 to 2003 (25.7 ± 8.36%, n=27), averaging 12.1% across the study period (Table 2, Figure 4). Unhealed high probability injuries were detected in the overall sample at annual frequencies ranging from 6.8 ± 3.59% (n=13, 2006) to 18.8 ± 4.16% (n=64, 2003), and averaged 11.1%. Annual variation was statistically significant for both metrics (Table 2), apparently due to the high value in 2003. The metrics also followed similar trends, although the one based on unhealed injuries was based on larger sample sizes and therefore more precise. When the two types of data were combined, at least 156 events involved 147 individuals during the study period.

Individuals with inferred entanglement injuries were demographically comparable to whales with documented entanglements during the same time period (Table 3). There was a significantly higher incidence of unhealed injuries among known and presumed juveniles (24.0%, n=72) than adults (16.0%, n=101, G=11.27, d.f.=1, p=<0.001). There were no significant differences in the frequency of unhealed injuries between adult females (14.4%, n=58) and adult males (15.7%, n=42). Although there appeared to be evidence of a higher entanglement rate among both juveniles and adults in 2003, it appeared to be significant only for the larger sample of adults (Figure 5). Most of the individuals that acquired a high probability injury had no other documented incidents on record since 1997. In total, 28 individuals acquired new scar evidence of entanglement at least twice since 1997, three were entangled at least three times and one was entangled at least four times.

Entanglement mortality

Mortality counts estimated from scar-based entanglement rates are shown in Table 4. Calculations were based on the frequency of unhealed injuries, as these estimates were comparable to, but more precise than inter-annual entanglement rates. Mortality was estimated for each year independently in light of annual differences in entanglement rates. Assuming a minimum population estimate of 549 whales (Waring *et al.* 2007) and a scar-based entanglement rate of 18.8%, approximately 103 Gulf of Maine humpback whales were estimated to have survived entanglement in 2003. If survivors represented 76.6% of the entanglements that occurred (calculated from Glass *et al.* 2008, Tables 1 and 2), then there were approximately 135 entanglements that year, of which 32 were lethal. However, photo-identification research indicates that at least 783 Gulf of Maine humpback whales were alive in 2003. Use of this minimum population size produced a higher estimate of 45 entanglement mortalities per annum. Finally, if there were 847 Gulf of Maine humpback whales in 2003, these data suggest that 49 entanglement deaths may have occurred that year. However, 2003 exhibited the highest estimated entanglement rate and therefore the highest estimates of mortality. When calculated across the study period, mortalities averaged 18.8 to 29.3 whales per year, depending on the assumptions of population size. As shown in Table 4, these estimates exceeded eye-witnessed serious injuries and mortalities along the US East Coast during the same period, as well as PBR.

Entanglement events and reporting

A total of 156 unique entanglement events were inferred from new injuries detected in the Gulf of Maine between 2003-2006. During the same period there were 56 confirmed reports of live humpback whale entanglements along the entire US East Coast (Glass *et al.* 2008). Only nine of the scar-based events corresponded to eye-witnessed cases, indicating a successful reporting rate of 5.7% for Gulf of Maine humpback whales during this period. When scar-based and eye-witnessed entanglement information were reconciled, at least 203 entanglement events were newly detected during the study period.

DISCUSSION

Entanglement is a documented human source of injury and mortality to humpback whales in US waters. Since 1997, a scar based research program has been undertaken annually in the Gulf of Maine to provide additional data on humpback whale entanglement. Unlike witnessed entanglements, scar-based monitoring can produce large annual sample sizes under a known level of effort, thereby allowing entanglement frequency to be estimated. Initially, scar-based inference was limited to the composite pattern of injuries obtained over the lifetime of the whale. However, with the accumulation of data and baseline coverage for a large portion of the population, these techniques have gradually been refined. It is now possible to narrow the period of injury acquisition to within 1-3 years in most cases and to reliably recognize injuries from the most recent events without baseline coverage. Perhaps most importantly, methods have been developed to estimate entanglement mortality based in part on scar-based studies of entanglement survivors. This report focuses on scar monitoring results from 2003-2006 and these new methodological approaches.

Entanglement frequency

Scar-based monitoring continues to suggest high rates of entanglement among Gulf of Maine humpback whales. This is reflected in a high probability of prior entanglement among whales entering the study, and the subsequent acquisition rates of both adults and juveniles. Even when the lowest possible population size is assumed, the average inter-annual entanglement estimate for this period (12.1%) corresponds to approximately 66 entanglement cases per year. Inter-annual estimates of entanglement during this period (6-26%) were not significantly different from those reported in previous years (8-25%, Robbins and Mattila 2004). There was, however, evidence of significant annual variation, primarily due to a high frequency of new injuries detected in 2003. This was evident in both metrics and both age classes, but significant only among the larger sample of adults. There were also slightly more adults involved in both inferred and documented entanglements during this period than in 2002-2004 (see Robbins and Mattila 2004, Table 5). However, both sources of data continue to indicate that juveniles remain at higher risk of entanglement.

Two methods were used to estimate annual variation during this study period. Inter-annual entanglement rates have been calculated previously, and provide accurate information on injury acquisition for individuals with the proper photographic coverage. This process of direct comparison of tail stock images from consecutive years is more accurate than inferring entanglement history from composite injuries. However, this approach is not necessarily unbiased because some individuals may be more likely to be re-sighted or adequately documented. Differential probability of encountering individuals and obtaining samples is a known source of bias in photo-identification studies and a potential concern for scar-based monitoring as well. Demographic bias is particularly likely because calves are excluded and juveniles are less likely to have prior baseline coverage than older whales. The latter is particularly problematic given that juveniles appear to be at higher risk of entanglement and so should be a priority for monitoring. The inter-annual comparison approach also takes advantage of only a fraction of the data obtained each year, depending on the number of animals re-sighted from one year to the next.

Robbins and Mattila (2004) previously reported on the potential for unhealed injuries to be used to detect entanglement events. It has subsequently been confirmed that most unhealed injuries that could be tracked had been obtained within a year of first detection. However, there are some notable exceptions, as larger injuries in particular sometimes require longer periods to heal. High quality, color imagery is also critical for the correct interpretation of unhealed entanglement injuries. This is now readily available thanks to modern digital technology, but the results can not be reliably compared to early work that was done exclusively with black and white film. Nevertheless, tracking of unhealed injuries appears to offer a second, independent measure of entanglement frequency. In this study period, it produced results that were consistent with inter-annual comparisons, but with more precision because estimates based on unhealed injuries involved larger sample sizes. However, if temporal variation is of interest, this approach requires sampling at an annual frequency to allow entanglement injuries to be detected before they heal. The inclusion of unhealed injuries is also promising avenue for less well-studied populations because it does not require a previous sample of the same individual. We recommend first screening such populations based on a combination of composite and unhealed injuries, for an initial indication of entanglement rates in the long- and short-term.

In the future, entanglement frequency in the Gulf of Maine will be estimated by mark-recapture statistical analyses. These techniques have the potential to take better advantage of the available data, while accounting for variation in individual detection probabilities. Scar-based inference is also expected to improve on-going studies of survival from witnessed entanglements. The survival rate of entangled whales is best understood when compared to unexposed individuals from the same population. Scar-based inference can help to improve that inference by identifying animals that were involved in unobserved events.

Systematic caudal peduncle monitoring has recently been prioritized in scar-based studies of North Atlantic right whales, for which it was concluded to be more accurate and precise than attempting to track entanglement injuries across all body parts (Knowlton *et al.* 2005). This has the added advantage of facilitating comparisons to systematic scar-based studies of Gulf of Maine humpback whales. Between 1997-2004, inter-annual entanglement rates of right whales were reported to range from 15-30% (Knowlton *et al.* 2008), which is within the confidence intervals of our results during the same period. Yet, the specific inter-annual patterns observed were not comparable between species. In particular, entanglement frequency was highest for humpbacks from 2002 through 2003, while this was one of the lowest reported periods on record for North Atlantic right whales (Knowlton *et al.* 2008). Such differences are not unexpected given that humpback and right whales use different Gulf of Maine habitats, as well as different areas outside of the Gulf of Maine in winter. Entanglement risk is expected to vary with the degree of overlap between whales and fisheries, and this is one of several issues that remains poorly understood for large whales. Scar based inference has the potential to contribute information on spatial risk because samples can be stratified by area, with a known amount of sampling effort. Like most spatial analysis, its validity depends upon the assumption that humpback whales acquired their injuries where they were sampled. Thus, the usefulness of this approach increases as we continue to narrow the time frame of injury acquisition for individual whales.

Entanglement reporting rate

As in previous years of this study, very few of the entanglement injuries observed on free-ranging animals corresponded to adequately documented events witnessed in progress. These results are consistent with findings that entangled whales outfitted with highly visible and marked telemetry buoys are rarely reported by observers (Landry *et al.* 2007). Both sets of data emphasize the continued importance of preventing entanglement rather than relying entirely on disentanglement to mitigate large whale entanglements.

Entanglement mortality

As noted in previous reports, scar-based entanglement monitoring has the potential to under-estimate entanglement frequency because the caudal peduncle is not always involved, some injuries heal before they are detected and some individuals die before they can be documented. Additional data and refinements have allowed us to narrow the time frame of entanglement estimates and to minimize the confounding effects of healing. Perhaps more importantly, we have developed an approach for estimating entanglement mortality based on scar-based studies of entanglement survivors.

The only previously published estimate of entanglement mortality rate for Gulf of Maine humpback whales was 0.2-0.3% for the period 1975-1990, based on a single documented entanglement death and various assumptions about the population (Volgenau *et al.* 1995). Population impacts are also quantified annually by NMFS, based on observed entanglement deaths as well as other witnessed cases considered likely to lead to death (Waring *et al.* 2007; Glass *et al.* 2008). However, as noted above, scar-based inference indicates that entanglements are rarely detected in progress. In addition, some may have a higher likelihood of detection based on their severity, location, time of year, gear configuration or other factors. The likelihood of detecting a whale after death is also not known, but likely to be low and variable. For example, Landry et al. (2008) reported on a marked right whale carcass that was confirmed to have been at sea for 88 days without detection. It is not known whether the carcass was visible at the surface throughout that period, but the finding raises the possibility that carcasses may be at sea for extended periods without being seen. Given these uncertainties, assessments that are based on a well-documented subset of eye-witnessed cases likely under-estimate the number of events and therefore the total effect on the stock. An alternate, less conservative approach is one that extrapolates observed events to the overall population.

Scar-based studies on free-ranging whales focus almost exclusively the survivors of entanglement. However, if the frequency of non-lethal entanglement events can be estimated, then the two pieces of information can be used together to estimate entanglement mortality. For the period 2003-2006, this approach suggests an average of approximately 19-29 deaths per year, or an entanglement mortality rate of 3%. By contrast, there were only three observed humpback whale mortalities attributed to entanglement and eight injuries thought to lead to mortality during the study period, or 2.8 total cases per year (Glass *et al.* 2008). Thus, our estimates are nearly an order of magnitude higher than the data that is currently used to evaluate impacts on the stock.

Despite its magnitude, the level of entanglement mortality estimated by this technique is within the bounds of population vital rates. For example, Clapham et al. (2003) estimated a non-calf survival rate of 95% for the period 1992-2002 and subsequent studies have further confirmed that first year survival can be on the order of 70% or less (Rosenbaum *et al.* 2002; Robbins 2007). Assuming that entanglement and related mortality acts preferentially on juvenile whales, then the mortality counts and rate estimated here are within the bounds of plausibility. In fact, Robbins et al. (2008) reported preliminary evidence that entangled Gulf of Maine juveniles had a lower survival rate than juveniles that had not been entangled. The biological impact of this number of deaths can be judged against the current Potential Biological Removal (PBR) value for this stock, as calculated by the National Marine Fisheries Service. For a population size of 549 Gulf of Maine humpback whales, the annual number of human-caused mortalities should not exceed 1.1 (Waring *et al.* 2007). These results suggest that humpback whales far exceed PBR. All other things being equal, an entanglement mortality count that is equal or less to PBR would appear to require non-lethal entanglement rates of less than 1%.

These mortality estimates are limited by the precision and accuracy of all input data, including non-lethal entanglement rates, the ratio of entanglement survival and the population size. Each of these parameters has its own measurement error and this will be reflected in the ultimate estimate. Additionally, scar-based entanglement rates likely over-estimate survival because animals with entanglement injuries may still die after they are observed, and this has yet to be estimated. The ratio of entanglement survival to mortality is another key piece of information, but presently based on relatively little data and with a likely bias toward survivors.

Finally, population size has been difficult to estimate for this population. Here we provided a less conservative minimum estimate of abundance (783 individuals in 2003) based on independent photo-identification studies. We consider this to be the best recent minimum estimate of population size, with three important caveats. First, this total includes individuals that have also been matched to other North Atlantic feeding areas, and so may not be true or consistent members of the Gulf of Maine stock. The total number of “transients” represented in these data has yet to be determined. Secondly, there was an unusual mortality event in the Gulf of Maine in 2003, and humpback whales were one of the affected species. Given that 2003 was the target year for our calculation, it is possible that this total includes a higher than average number of individuals that subsequently died in that same year. Finally, the “minimum number alive” is depends heavily on the amount of photo-identification data available before, during and after the target year. Thus, this total should not be directly compared to other “minimum number alive” values without accounting for the extremely high level of effort that contributed to this result.

In conclusion, scar-based monitoring to date has provided key information on entanglement rates, entanglement reporting rates and mortality. In spring 2009, NMFS will require coast-wide modification to ground line in an effort to reduce the large whale entanglement rate. This change has the potential to reduce entanglement rate for humpback whales, but the magnitude of the possible effect is not yet known. Scar based approaches should therefore prove valuable for tracking the effectiveness of this management action and others in the future.

Figure 1: Body areas examined during this study, including the peduncle flank, the leading edges of the flukes, the dorsal and ventral peduncle. The left leading edge and left flank are not visible in this image. The image represents the preferred angle and distance for sampling.

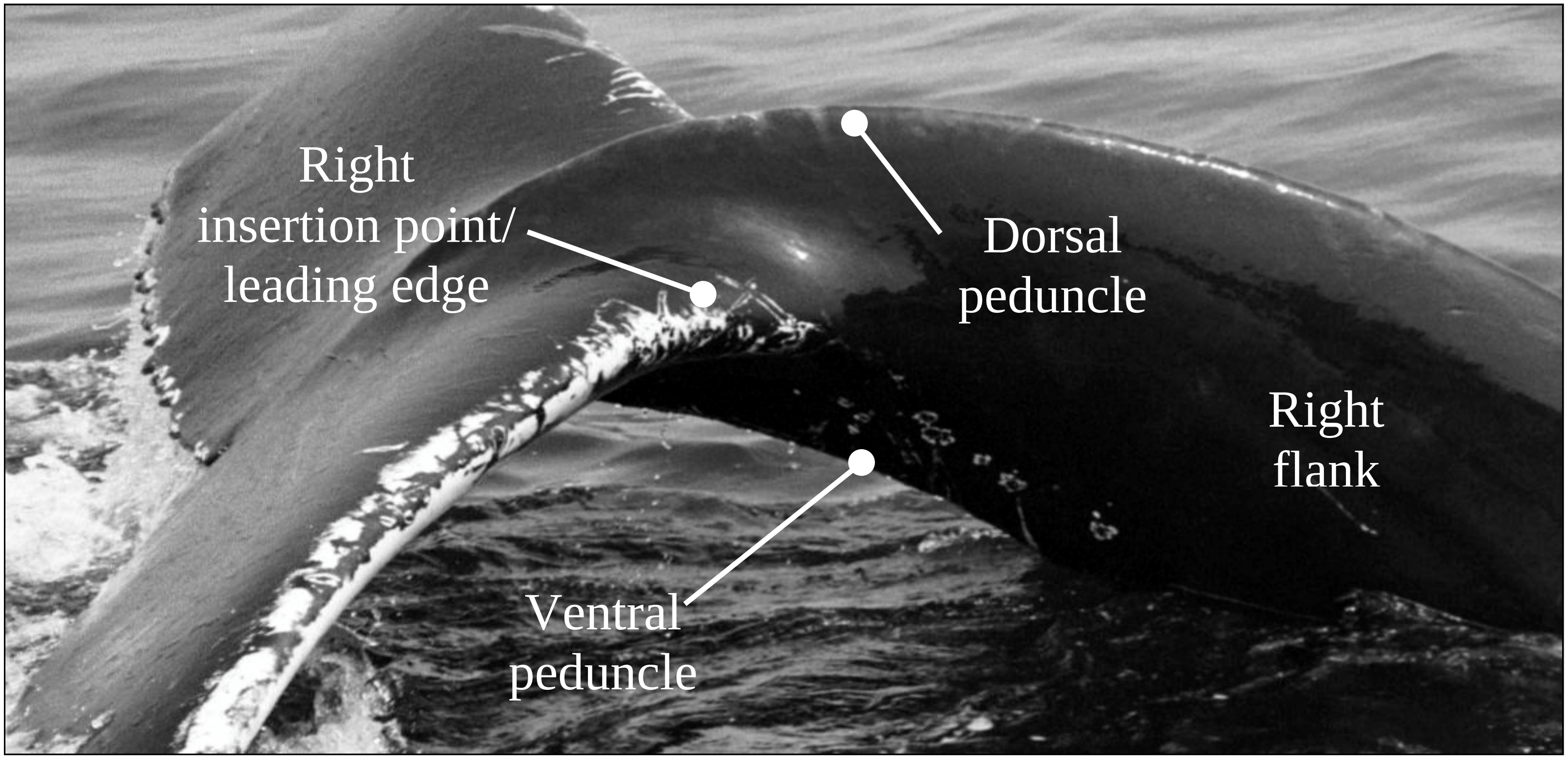

Figure 2: Examples of unhealed caudal peduncle/fluke injuries produced by four documented entanglement events during the study period. Note the presence of wrapping injuries, notches or deformation in at least two coding areas in all cases. In the lower right image, the flukes (white material) were necrotic due to a tight entanglement at base of the caudal peduncle. Images were taken under NOAA permit 932-1489.

Figure 3: Examples of scar interpretation from the caudal peduncle and flukes of four individuals. Note wrapping scars, notches and other injuries in at least two areas in all inferred entanglement cases.

a) No scarring indicative of entanglement.

b) Healed entanglement-related injuries.

c) Unhealed injuries indicative of a recent entanglement.

d) Partially healed entanglement wounds (1) with new unhealed injuries from a subsequent event (2).

Figure 4: Inter-annual acquisition of entanglement scars, 1997-2006. Error bars represent the 95% confidence interval of the percentage. Results for years ending 1998-2002 were taken from Robbins and Mattila (2004). The dashed line represents the mean value (12.1%) across this ten-year period.

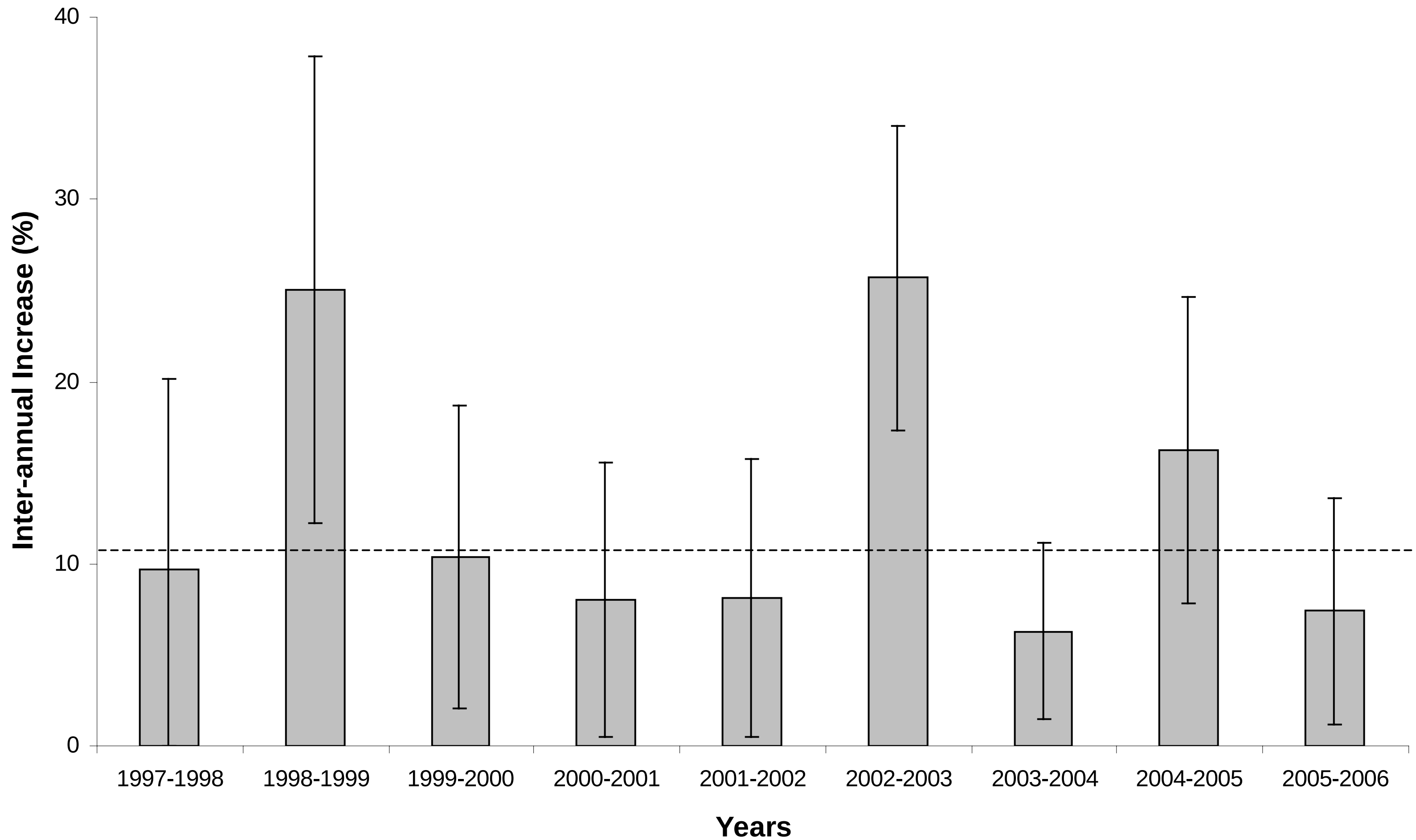

Figure 5: Frequency of unhealed injuries by year and age class, 2003-2006. Error bars represent the 95% confidence interval of the percentage. As a whole, juveniles were more frequently entangled than adults, and both classes exhibited their highest values in 2003. However, only adults exhibited significant annual variation in entanglement frequency during the study period.

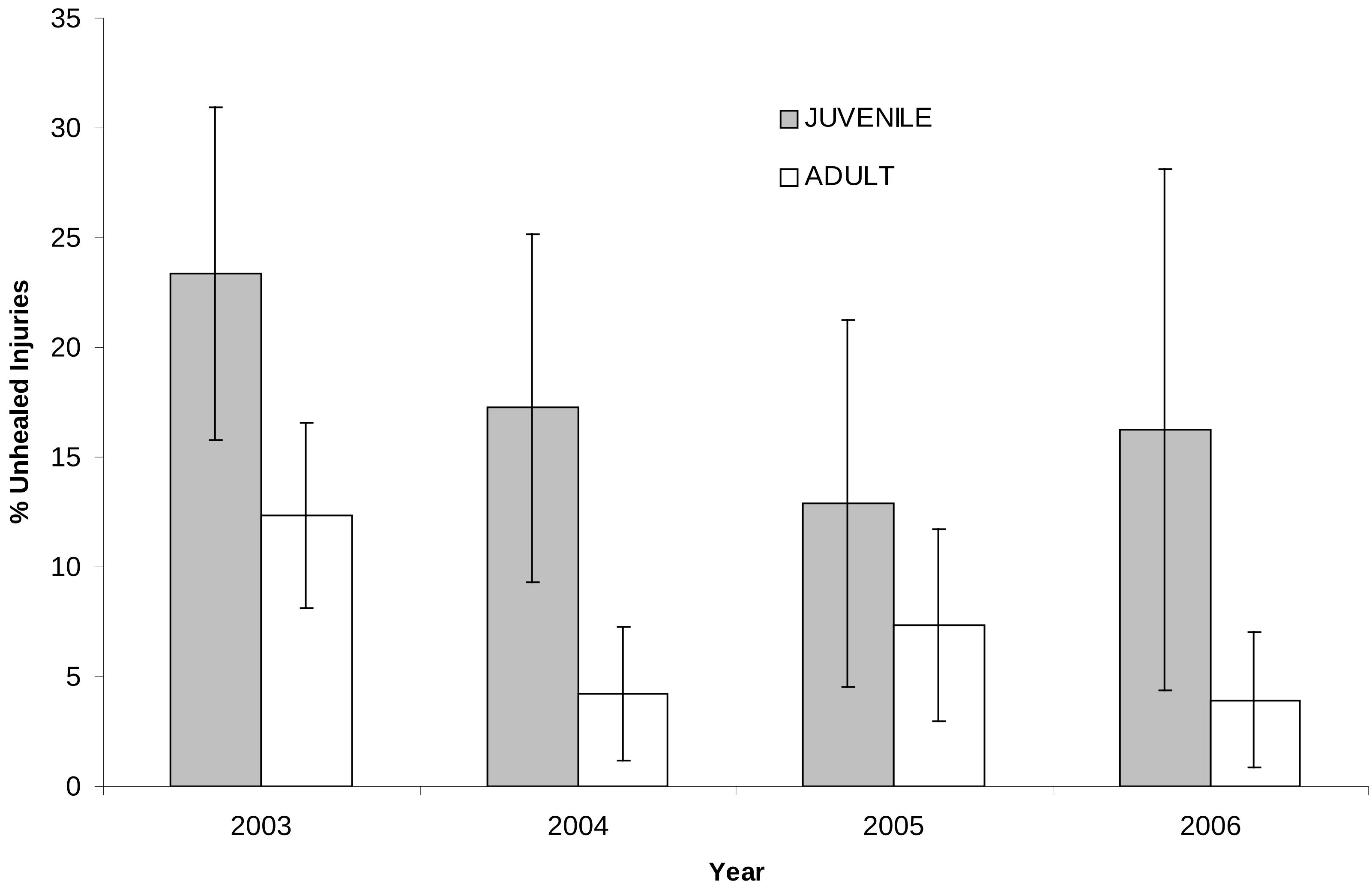

Table 1: Annual summary of the number of images obtained and the number of unique individuals represented. The total number of individuals that were new to the study is also shown by year, along with the percentage of data obtained from opportunistic platforms.

Year	**Number of images**	**% whalewatching**	**Number of individuals**	**New to the study**
2003	908*	46.9%	340	171
2004	463	41.7%	247	109
2005	389	49.1%	196	66
2006	395	43.5%	190	66
Total unique	2,155			

*Effort in 2003 was enhanced by the MONAH project

Table 2: Annual frequency of entanglement injuries by type of detection, 2003-2006. The number of individuals with new injuries is shown in parentheses. Annual variation was significant for both metrics.

Year	**Not present in previous year**	**Unhealed**	**Total Combined Events**
2003	25.7 ± 8.36% (27)	18.8% ± 4.16 (64)	76
2004	6.3 ± 4.83% (7)	8.5% ± 3.28 (21)	30
2005	16.2 ± 8.40% (12)	10.7% ± 4.33 (21)	33
2006	7.4 ± 6.20% (5)	6.8% ± 3.59 (13)	17
Average	12.1% (52)	11.1% (119)	156
Test of Annual Variation	G=21.17, df=3 p<0.001	G=21.88, df=3 p<0.001	

Table 3: Demographic comparison of inferred and documented entanglements, 2003-2006. Percentages were calculated across class, based on the total number of high probability injuries and documented entanglements, respectively. Scar-based research produced results comparable to documented entanglements, but with larger sample sizes.

Class	**High probability injuries[1]**	**Documented entanglements**
Calf	9.6% (15)	10.0% (3)
Juv+Unk	33.8% (53)	40.0% (12)
Mature	56.7% (89)	50.0% (15)
Female[2]	52.5% (74)	48.1% (13)

[1]Injuries acquired after a baseline sample or unhealed during the sampling period.
[2]Excluding animals of unknown sex

Table 4: Estimated number of entanglement mortalities (N_{ME}) relative to the number of observed mortalities (N_{MO}) and Potential Biological Removal (PBR), 2003-2006. Mortalities were estimated based on annual scar-based entanglement rates, three population size (*Nt*) estimates and assuming a constant entanglement survival frequency of 76.6% (see methods for formula). Mortality estimates were higher than both eye-witnessed serious injuries/deaths and PBR during the same period.

Interval End	Scar-based Entanglement Rate (%)	N_{ME} [1] (Best [Min,Max]) *Nt*=549	N_{ME} [1] (Best [Min,Max]) *Nt* =783	N_{ME} [1] (Best [Min,Max]) *Nt* =847	N_{MO} [2]
2003	18.8 ± 4.16	32 [25,39]	45 [35,55]	49 [38,59]	5
2004	8.5 ± 3.28	14 [8,20]	20 [12,29]	22 [14,31]	2
2005	10.7 ± 4.33	18 [11,25]	26 [15,36]	28 [17,39]	0
2006	6.8 ± 3.59	11 [6,18]	16 [8,25]	18 [8,27]	4
Total		75 [50,102]	107 [70,145]	117 [77,156]	11
Average		18.8	26.8	29.3	2.8
PBR[3]		1.1	---	---	---

[1]The number of entanglement mortalities was estimated for each value of *Nt* based on the point estimate of the entanglement rate (Best) and its lower (Min) and upper (Max) confidence limits.
[2]Taken from Glass *et al.* (2008) for the entire US East Coast
[3]Potential Biological Removal (PBR) value for *Nt* =549 as reported by Waring *et al.* (2007).

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