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Vessel collision injuries on live humpback whales, *Megaptera novaeangliae*, in the southern Gulf of Maine

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Abstract

North Atlantic humpback whales (*Megaptera novaeangliae*) in the Gulf of Maine overlap with both recreational and commercial vessel activity. Vessel strikes are one source of anthropogenic impact that has the potential to inhibit the recovery of this protected species. There are currently no regulations or guidelines specifically devised to reduce the likelihood of collisions for vessels transiting in the vicinity of humpback whales, except for vessels actively engaged in whale watching. To better understand interactions between vessels and humpback whales, we analyzed injuries on 624 individuals photographed in the southern Gulf of Maine from 2004 to 2013. Multiple reviewers evaluated 210,733 photos for five categories of injury consistent with a vessel strike. In total, 14.7% (n = 92) of individuals photographed showed injuries consistent with one or more vessel strikes. These results likely underestimate vessel collision rates and impacts because multiple events, events resulting in mortality, and those that involved only blunt force trauma could not be detected. Nevertheless, our results indicate that vessel strikes are underreported and that healing is dependent on the severity and location of the injury. We recommend that a management strategy be developed for all classes of vessels transiting in the vicinity of whales.

Key words: vessel strike, humpback whale, Gulf of Maine, Stellwagen Bank National Marine Sanctuary, marine conservation, scar, photo-identification, wound, healing.

The Gulf of Maine (GoM) is the southernmost primary feeding ground for humpbacks in the North Atlantic Ocean and individuals and overlap with both recreational and commercial vessel activity. At the time of this study, humpback whales were listed as endangered under the U.S. Endangered Species Act and considered a strategic stock under the U.S. Marine Mammal Protection Act. Strategic stocks are defined as those for which the rate of direct human-caused mortality exceeds the designated potential biological removal (PBR) level (16 U.S.C. § 1362 [19]). Observed mortalities and injuries from anthropogenic causes may be inhibiting recovery of this protected species (Waring *et al.* 2014), and these events are likely underestimated due to undetected events, limited carcass recovery and necropsy effort, and difficulty in assessing cause of death when carcasses are examined. Cause of death was determined for less than half of all reported humpback whale carcasses observed on the U.S. East Coast between 1970 and 2009 (van der Hoop *et al.* 2013). When cause of death was determined, 74% were attributed to human activities, including ship strikes (van der Hoop *et al*. 2013).

In 2008 the National Marine Fisheries Service (NMFS) implemented the Final Rule to implement speed restrictions to reduce the threat of ship collisions with North Atlantic Right whales (U.S. Federal Register 2008), codified at 50 C.F.R. § 224.105 (2008). These seasonal management areas, which require vessels greater than 20 m to travel at ≤10 knots, were designed for North Atlantic right whales, but proposed to provide ancillary benefit to other large whales, including humpback whales. While the seasonally managed areas covered by the “Speed Rule” were found to reduce collision risk with North Atlantic right whales, Laist *et al.* (2014) found that humpback whales did not significantly benefit. Similarly, van der Hoop *et al*. (2015) did not detect significant reduction in ship strikes of large whales either spatially or temporally following the implementation of the seasonally managed ship speed rule.

Currently, in NOAA's Northeast Region (Maine through Virginia), there are guidelines for vessels engaged in whale-watching to avoid harassment and possible injury (U.S. Federal Register 1999). These voluntary guidelines were developed in 1985 (revised in 1998) as a result of vessel strikes by commercial whale-watching vessels and included input from the commercial whale-watching owners and managers. Wiley *et al*. (2008) found that commercial whale-watching vessels did not fully comply with the speed portion of the guidelines, yet also concluded that no whales were struck by commercial whale-watch vessels during the study period. However, the latter depends entirely on reporting by vessels involved in strikes and by those that witness events. Limitations on event detection and reporting have prompted injury-based studies of entanglement rates (Robbins and Mattila 2001, 2004; Robbins 2009, 2012). However, to date, there has been no systematic effort to quantify nonlethal vessel-related injuries on Gulf of Maine humpback whales.

This study analyzes images for injuries consistent with vessel strikes in order to address the following objectives: (1) to estimate the percentage of humpback whales in the southern GoM that have apparent vessel-strike injuries, (2) to analyze the apparent vessel-strike data in conjunction with demographic data to identify any particularly vulnerable demographic component of the population, (3) to characterize the body location and severity of observed injuries and to monitor healing and clarify definitions on healing, and (4) to review management efforts and outreach for vessels transiting in the vicinity of whales in the southern GoM and recommend modifications to monitoring and management.

Methods

Data Sources

This study focused on 210,733 high-resolution digital images of 624 individual humpback whales. Images were collected by the Whale and Dolphin Conservation aboard commercial whale-watching boats and research vessels in and around the Stellwagen Bank National Marine Sanctuary, in the southwest GoM, from 2004 through 2013. They were obtained primarily for photo-identification purposes with an emphasis on ventral fluke and dorsal fin images, but other body parts were also documented opportunistically. Individual identifications and data on sex and age class were facilitated by the Gulf of Maine Humpback Whale Catalog curated by the Center for Coastal Studies (Provincetown, MA).

Vessel-strike Injury Analysis

Protocols for detecting and assessing vessel-strike injuries were adapted from studies of North Atlantic right whales (Knowlton and Costidis 2013) and gray whales (Bradford *et al.* 2009). The body was divided into 26 body regions for coding purposes (Fig. 1). A scoring opportunity was defined as the ability to code a body zone in a given photograph. Photographic coverage was determined to be "full," "partial," or "none" for each of the body regions, given all photos available for the individual. In order for coverage of a given zone to be considered "full," the entire zone must have been clearly visible in photographs of adequate quality (reasonable distance and clarity). Anything less than full coverage of a zone was deemed "partial" coverage. Zones rated with "full" coverage were used to determine whether a vessel-strike injury existed in that zone (yes/no) and "partial" coverage zones were rated as either yes or unknown for scar presence. Body zones could potentially have more than one vessel-strike injury in or across multiple body zones. Cases in which there were vessel-strike injuries across multiple zones did not automatically qualify the injury as resulting from a separate vessel-strike event. These injuries, if not obvious by continuity of the wound/scar, were then scored for state of healing appearance.

Vessel-strike Injury Definitions

In order for the injury to be attributed to a vessel strike, the wound had to meet one of five mutually exclusive categories: (1) consistent with propeller; (2) probably due to propeller; (3) consistent with skeg + propeller; (4) other physical vessel trauma; or (5) other possible vessel-strike injuries, defined as follows:

Consistent with propeller and probably due to propeller—Relatively parallel wound pattern with evenly spaced incisions; these injuries can vary in size, appearance, and severity depending on the size of the vessel, the speed of the boat, and the position of the animal in the water column (Fig. 2A).

Consistent with propeller + skeg—An injury with relatively parallel evenly spaced incisions with a singular straight wound/scar adjacent to the propeller incisions. The singular straight injury (skeg wound/scar) will be nearly perpendicular to the parallel evenly spaced incisions (propeller wound/scar) and may extend the full or partial length of the propeller incisions (Fig. 2B).

Other physical vessel trauma—Other injuries that appear to be the result of physical trauma from either a pointed object or a sharp edge or from a blunt force, other than those described above. Wounds inflicted from other physical trauma are often "lumpy" in appearance with irregular edges once healed (Fig.

2C).

Other possible vessel strike injuries—Other injuries that could not be confidently assigned to one of the previous definitions, but were not consistent with social, foraging, or entanglement injuries and may have been the result of a vessel strike (Fig. 2D).

After the injury type was categorized, its severity and healing states were evaluated. Severity was determined by the body layers affected as follows: (1) penetration only of the skin, (2) penetration of the skin and blubber, and (3) penetration into muscle or deeper. State of healing was categorized at each observation as fresh/recent, healing, or healed, as defined in Table 1.

For each of the 26 body zones, dates were noted for when the scar/wound was first sighted and the date on which each photo was taken. The age class of the animal at the time the vessel-strike injury was determined following previous humpback whale studies in the GoM (*e.g.*, Clapham 1993, Robbins 2007). Age classes were defined as follows: dependent calves (<1 yr old), independent juveniles (known to be 1–4 yr old), and adults (≥5 yr old). Cases in which wounds had healed prior to the first sighting of the injury, or the age of the individual was not known, categorized as age class "unknown" for this analysis.

Statistical Analyses

A chi-square test for independence was used to determine whether vessel-strike injury presence differed among the factors sex, age class, and body region.

Interrater Agreement

A primary and secondary reviewer independently coded all suitable photos collected from 2004 to 2011 using the vessel-strike injury analysis protocols as outlined above. Both reviewers had previous marine mammal photo-identification experience. Images for 2012–2013 were analyzed by the same primary reviewer and three secondary reviewers (reviewers 2a, 2b, and 2c) with photo-identification experience ranging from <1 to >2 yr. All reviewers were trained using the same techniques and protocols as outlined above for the study. This technique was used to test the agreement and ability to have multiple researchers analyzing data in the future and to test the strength of the injury-type definitions developed for this study.

Krippendorff's alpha (α) was used to measure the agreement between the reviewers. This statistic is a reliability coefficient developed to measure agreement between independent coders (Krippendorff 2007). Krippendorff's alpha is a generalization of several known reliability indices and enables a variety of data with the same reliability standard to be ranked. Krippendorff's alpha can be used for both large and small sample sizes, any number of categories, levels of measurement, and accounts for incomplete or missing data (Hayes and Krippendorff 2007). The basic form of the equation is

$\alpha = 1 - \frac{D_o}{D_e}$, where D_o is the observed disagreement and D_e is the disagreement one would expect when the coding of units is attributable to chance. When observers agree perfectly, $D_o = 0$ and $\alpha = 1$, (Krippendorff 2007). Krippendorff suggests the following for interpreting his coefficient: "It is customary to require $\alpha \geq .800$. Where tentative conclusions are still acceptable, $\alpha \geq .667$ is the lowest conceivable limit"

(Krippendorff 2004, p. 241).

Following interrater agreement tests, reviewers discussed all disagreements of injuries and injury type. The reviewers defended the rating they gave and referred back to definitions for support. The primary reviewer and second reviewer(s) came to consensus for the final calculations of the data analysis.

Results

Interrater Agreement

The data analyzed included 624 individuals, resulting in 16,224 scoring opportunities for both the primary reviewer and the second reviewer. Overall, reviewer 1 and reviewer 2 agreed 83.5% of the time for vessel-strike injury presence (α = 0.707; *n* agreements = 13,539; *n* disagreements = 2,685). As more than one reviewer 2 was used for the analysis of the 2012–2013 data, each reviewer 2 was analyzed independently against reviewer 1. Reviewer 2a agreed 83.1% (α = 0.704), reviewer 2b agreed 83.4% (α = 0.705) and reviewer 2c agreed 84.0% (α = 0.712) with reviewer 1 for the presence of vessel-strike injuries. Agreement of vessel-strike injury presence for the rating of “yes” was particularly strong with 99.3% agreement between the primary and all secondary reviewers combined.

Overall, reviewer 1 and reviewer 2 agreed 99.3% of the time on the decision of injury type (α = 0.627; *n* agreements = 16,116; *n* disagreements = 108). Reviewer 2a agreed 99.5% (α = 0.651) with reviewer 1. Reviewer 2b agreed 99.3% (α = 0.70) and reviewer 2c agreed 99.2% (α = 0.514) for the decision of injury type against reviewer 1.

Photographic Coverage of Body Zones

Of the 624 analyzed individuals, 11.8% (*n* = 53) had full photographic coverage of all dorsal and ventral regions while

64.8% (*n* = 398) had full photographic coverage of all dorsal zones posterior to the blowhole through the tailstock (Fig. 3). Photographic coverage was most complete for dorsal regions and both the dorsal and ventral fluke. The ventral fluke was the most photographed zone, due to it being the primary photo-identification feature. The ventral tail stock was the most predominant zone rated “partial” coverage (Fig. 4). Photo coverage was consistently limited for the pectoral fins and all ventral regions except the ventral flukes. The dorsal side of the pectoral fin was the only dorsal zone that was not partially or fully photographed in at least 50% of the individuals. Full photographic coverage was available for 4,427 scoring opportunities on the left side body zones *vs*. 4,462 scoring opportunities for the right side body zones. Partial photographic coverage was determined for 538 scoring opportunities for the left side body zones *vs*. 513 scoring opportunities for the right side body zones. No photos were recorded for 3,134 scoring opportunities on the left side body zones *vs*. 3,124 scoring opportunities on the right side body zones.

Vessel-Strike Injuries

Out of the 624 individuals reviewed, 14.7% (*n* = 92) of whales had injuries consistent with at least one vessel strike, with a total of 149 injuries documented. The number of vessel-strike injuries per individual ranged from zero to four. Of the individuals showing evidence of vessel strikes, most exhibited either one (*n* = 46) or two (*n* = 37) injuries, however, seven individuals had three vessel-strike injuries and two showed evidence of four vessel-strike injuries. In most cases it could not be determined whether multiple injuries in different body zones were caused by one or more event. However, one individual, a dependent calf, was confirmed to have injuries from two separate events. The two events were discriminated based on the presence of new fresh injuries in different body regions within weeks of when the calf was most recently documented with its initial healing injuries.

State of Healing

The 149 vessel-strike injuries were each categorized into one of the three healing states based on definitions in Table 1. In total, 10% (*n* = 15) were classified as fresh/recent at first sighting, 29% (*n* = 43) as healing, and 61% (*n* = 91) as healed. A total of 15 fresh/recent injuries were observed on nine individuals; of these nine individuals, five individuals (all calves) were documented in the study area without injuries between 6 d and 1 mo prior to the first date of detection. Fresh injuries were documented in 2008 (*n* = 4), 2009 (*n* = 4), 2011 (*n*=3), 2012 (*n* = 1) and 2013 (*n* = 3).

Severity of Injuries

Injuries were categorized as 29% (*n* = 43) penetrating skin only, 66% (*n* = 98) extending into blubber, and 5% (*n* = 8) extending into muscle.

Vessel-strike Injury Type

Vessel-strike injuries were assigned to one of five injury types based on definitions above and Figures 2A–2D: 12% (*n* = 18) were consistent with propeller wounds, 9% (*n* = 14) were consistent with skeg + propeller wounds, 8% (*n* = 12) were probable propeller wounds, 38% (*n* = 56) were deemed other physical vessel trauma and 33% (*n* = 49) were considered other probable vessel-strike injuries (Fig. 4).

Body Region

A total of 58% (n = 86) of vessel-strike injuries were located on the right side of the individual, 42% (n = 63) had injuries on the left side of the body. In addition, 21% (n = 32) had vessel-strike injuries on both sides of the body. A chi-squared test shows there was no significant difference in the number of right side *vs*. left side injuries χ^2 (1, n = 149) = 3.550, P = 0.059).

Zones 5R and 5L, comprising the flank region, were the body zones sighted most frequently with injuries from a vessel strike. Forty-six percent (n = 69) of all vessel wounds/scars were observed in zone 5 with 28% (n = 42) in 5R and 18% (n = 27) in 5L. Including only vessel-strike injuries consistent with propeller and consistent with skeg + propeller (excluding "probable" vessel-related injuries and other vessel-related injuries), zones 5 and 8 ranked highest with 62% and 16% respectively. Using a chi-squared test, we found significant differences between the locations of injuries between all zones (P < 0.001), with the highest percentage of injuries documented in zone 5. Zone 1R (right side of head) and 12L and 12R (pectoral fins), were the only observed dorsal zones where no vessel-strike injuries were observed (Fig. 5).

Identification of Vulnerable Demographics of the Population

Sex

Sex was known for approximately 68% of the individuals studied (n = 422) with a bias toward females. The frequency of vessel-strike injuries for females 19.0% (48/252) was not significantly different from males 16.5% (28/170) χ^2 (1, n = 76) = 3.16, P = 0.57).

Age Class

Of the 92 individuals with injuries consistent with vessel strikes, the age class at which they acquired the injury could be determined for 56 individuals: 55% were acquired when the whale was an adult (*n* = 31), 13% (*n* = 7) as a juvenile, 32% (*n* = 18) as a calf. Two mothers sustained injuries while accompanied by a dependent calf.

A chi-squared test indicated statistically significant differences in overall vessel-strike injury frequency χ^2 (2, *n* = 56) = 15.4, *P* < 0.0001) among adults (55% *n* = 31), juveniles (13%, *n* = 7), and calves (32%, *n* = 18).

Discussion

Injury-based assessments have been used to evaluate the frequency of entanglement among Gulf of Maine humpback whales (Robbins and Mattila 2001, 2004; Robbins 2009, 2012); however, this study is the first to analyze vessel-strike injuries systematically through photographs of humpback whales in this region.

Similar to a previous study (Bradford *et al.* 2009), two reviewers were used for interrater agreement to determine reliability of the findings and to determine whether protocols may be used by more than one qualified researcher and achieve similar results. This study also tested the methodology by using multiple second reviewers with varying degrees of photo-identification experience to assess the strength of the definitions developed for the study. Interrater agreement results indicated that once an individual has been trained, the level of prior research experience was not a factor in the ability to determine presence or absence of vessel-strike injuries and to rate types of scarring based on the definitions used in this study. This implies that more than one trained researcher may be used to produce comparable results if study protocols and definitions are followed.

The dorsal body regions that were most frequently observed with sublethal vessel-strike injuries were posterior to the pectoral fins through the tail stock. It is likely that surface exposure of the back, combined with the tendency to raise the tail stock prior to a dive, leave these regions most vulnerable. Because data were obtained opportunistically, it is possible that images of body parts, other than those used for photo-identification, were photographed more frequently if wounds were observed. However, as most (63.8%) of the individuals examined in this study had full photographic coverage of the dorsal region (posterior to the blowhole through the tail stock) it is unlikely that these data are biased by wound presence. The results of this study indicate that whales can be struck in any dorsal region. However, the frequency of injuries in the dorsal back and tail stock regions, and the high likelihood of these areas being photographed highlight the importance of these body regions. This suggests that in the absence of full body documentation, vessel-strike injury monitoring of these regions in particular could be beneficial in assessing the impacts of vessel-strikes in future studies.

Definitions of injury type and healing state used in this study were developed from and generally consistent with previous marine mammal anthropogenic injury studies (Bloom and Jager 1994, Visser 1999, Rommel *et al.* 2007, Bradford *et al.* 2009, Robbins 2012). According to Rommel *et al*. 2007, the skin over healed injuries should be stretched, smooth, and glossy tissue in appearance. However, our results indicate that smooth epidermal coverage is not in all cases an adequate indicator of a “healed” injury. In one documented case, the underlying shape of a vessel-strike injury to a caudal peduncle continued to change over a 47 mo time frame, even though full epidermal coverage with smooth tissue was noted within 15 mo of the injury. In this case, smooth, glossy tissue was not a good indicator because tissue continued to modify at the injury site. It is possible that deep injuries to the caudal peduncle, or other areas with flexure and movement, will take longer to heal (Zogaib and Monte-Alto-Costa 2011). Healing likely varies with the severity of the injury, placement of the injury, and the age of the animal. We recommend that a vessel-strike injury not be assumed to have healed until the appearance of the wound site remains unchanged. In the referenced case above, “healed” status was determined after the individual was documented with no changes in healing over a 2 yr period (see Appendix S1 and associated figures). However, future longitudinal studies of humpback whale vessel-strike injuries are needed to better quantify criteria for healing status.

As with healing, the severity of the injury cannot easily be determined by images alone. In this study, the majority (66%) of the injuries observed appeared to penetrate the blubber layer, with very few (5%) cases known to involve muscle. The few observed incidences of the latter may be due to a higher mortality from these types of injuries. As this was a systematic study of photographs of live animals, analyses were limited to those that the individuals were able to survive the vessel-strike injury. According to Laist (2001), most severe and lethal injuries result from collisions with large ships, whereas our sample set is most likely biased towards encounters with smaller vessel size classes. However, initially surviving a vessel strike does not guarantee that injury will not result in mortality later in the animal's life (Moore *et al.* 2007). Although the wound site might appear to be healing/healed or superficial, chronic exposure to stress in cetaceans may cause an imbalance in metabolic regulation which can lead to death (Angliss and Demaster 1998). In at least one mortality case, a humpback whale succumbed to an apparent infection from a vessel-strike injury that was documented as healed[2] and would likely have been classified as moderate in severity when the injury was first detected. This was known only because the whale was necropsied to determine its cause of death. Studies have shown that necropsies are necessary to accurately determine blunt force trauma (Wiley *et al.* 1995; Moore *et al.* 2004, 2013), but this case in particular provides an example of a mortality resulting from an injury that appeared to be superficial, or healed. Long-term studies underway on this population will help to clarify the ultimate fate of the individuals in this study relative to those that have not been exposed to a vessel strike.

At least 14.7% of southern Gulf of Maine humpback whales showed evidence of at least one injury consistent with a vessel strike. Because these data were largely based on opportunistic sightings taken from whale-watching vessels, it is conceivable that individuals that are more likely to interact with boats were photographed more frequently and these may also have a higher likelihood of vessel strikes. Alternatively, it is conceivable that these individuals have greater experience with vessels and so are more adept at avoiding collisions. In the future, the techniques used in this study can be applied to data from systematic population surveys to evaluate this question and to examine vessel-strike injuries at the population level in the GoM.

This study found that adult humpback whales are significantly more likely to acquire injuries from vessel strikes and have an overall higher frequency of such injuries. While we cannot definitively determine that risk is higher for adults, it may be a result of foraging behavior. Weinrich *et al*. (1997) found that adult humpback whales preferentially exploit prey in the upper water column, which may result in increased exposure to vessel activity. It is also important to consider that previous studies of humpback whales have shown no detectable reactions to vessels when whales were engaged in surface feeding or social behaviors (Krieger and Wing 1984, Baker and Herman 1989, Neilson *et al.* 2012). Furthermore, Friedlander *et al.* (2009) noted that humpback whale surface feeding behavior in the southern GoM was most likely to occur during daylight hours, a time when prey are more likely to be at the surface and, as supported by acoustic data, vessel density in the region is also likely to be highest (SBNMS). In contrast, when considering only fresh/recent injuries evaluated in the study, calves were more likely (56%) to exhibit wounds from vessel strikes, consistent with the findings of Laist *et al.* (2001).

Ten percent of the injuries were rated as fresh and were assumed to have occurred in the study region, as these individuals were documented in the study area without injuries between 6 d and 1 mo prior to the first date of detection. Because the images were not taken at standardized distance, photogrammetry scales could not be applied to estimate propeller wound dimensions and, therefore, vessel class sizes. Similarly, the activities in which the vessels were engaged when the strikes occurred cannot be determined. However, it is unlikely that the injuries were caused by either sovereign vessels, vessels engaged in commercial whale watching, or vessels carrying paying passengers as these vessel types have been shown to be more likely to report their strikes than other vessel types (Jensen and Silber 2003). Other vessels that could account for the unreported events documented in this study include commercial fishing, recreational vessels, and other small boaters. According to the Stellwagen Bank National Marine Sanctuary, more than 400 commercial fishing vessels operate in the southern GoM year round along with recreational boating and fishing vessels (SBNMS 2007). With more than 64 harbors and 80 yacht clubs in Massachusetts alone, the Sanctuary estimates that hundreds of small boaters operate within the Sanctuary waters daily during the summer, a time when humpback whales are most likely to be present (SBNMS 2007).

Between 2004 and 2013, NOAA’s Northeast Region’s Office of Law Enforcement had only received one report of a vessel strike (initially reported as harassment) involving a humpback whale.[3] This collision did not result in sharp force trauma and, as a result, was not part of this study. Therefore, none of the injuries analyzed in this study were reported to NOAA. Laist *et al.* (2001) found that for vessels <24 m in length it is highly unlikely that the collisions go undetected by the operator, as vessel damage tends to be significant for this size class. A study of reported whale-vessel collisions in Alaskan waters by Neilson *et al.* (2012) further supports these claims; the study reports one-third of collisions resulted in some kind of human toll and/or property damage. This raises the question of whether the lack of reporting a vessel collision with a whale is due to the fact that boaters are unaware they have struck a whale, perceived legal consequences, or ignorance of the requirement and method to report.

The 1998 revisions of the Northeast Regional Whale-Watching Guidelines included the development of "speed rings" specifically designed to reduce the risk of collisions when whale-watching vessels approach and leave large whales. The development and monitoring of these guidelines has focused exclusively on commercial whale-watching vessels (SBNMS Behavioral Disturbance Working Group Plan 2004, Wiley *et al.* 2008). According to NOAA (2010), recreational boaters are numerous and often aggressive in the Stellwagen Bank National Marine Sanctuary from May to September, the major portion of the whale-watch season. A public education program, "See a Spout, Watch out!" was developed by Whale and Dolphin Conservation, in conjunction with NOAA, in an attempt to educate private recreational boaters that whale watch in the sanctuary. SBNMS recognizes that this is largely a land-based outreach program and an on-the-water program is needed to successfully increase outreach to vessels in the vicinity of whales (SBNMS 2007). The concern for vessels operating in the vicinity of whales (not including commercial whale-watching vessels) has been acknowledged by the SBNMS Advisory Council and the council has formally recommended that the Sanctuary support and develop research programs to reduce the risk of vessel strikes (SBNMS 2007). In August of 2015, the SBNMS piloted its Whale Outreach and Education Project with the specific purpose of conducting outreach and educating private boaters and whale watchers regarding the Northeast Regional Whale Watching Guidelines and best practices.[4] Continued monitoring of vessel-strike injuries will help to evaluate whether these management and outreach approaches will reduce the number of ship strikes or the reporting rates.

This study provides a minimum estimate of vessel strikes for humpback whales in the southern Gulf of Maine and provides evidence that these events are underreported. Further efforts should be focused on defining the vessel classes involved in these strikes, increasing rates of reporting, and analyzing the potential for impacts from injuries that are not immediately fatal. We believe that long-term studies of injuries on whales can be useful in monitoring the efficacy of existing guidelines/regulations. Results from wound studies can assist managers in evaluating their ability to meet the statutory goals put forward for protected species. We recommend that future guideline/regulation development should consider all vessels operating or transiting in the vicinity of whales, not only those engaged in whale watching.

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Figure 1. Twenty-six body zones used when coding for vessel interactions, adapted from Bradford *et al.* 2009 and Knowlton *et al.* 2013.

Figure 2. (A) Consistent with propeller and probably due to propeller, (B) consistent with propeller + skeg, (C) other

physical vessel trauma, (D) other possible vessel strike injuries.

Figure 3. Frequency of photo coverage: full, partial, and no photos of each body region (zone) (n = 624).

Figure 4. Relative percentage of vessel strike injuries occurring in each dorsal zone. The number of individual injuries are also noted (n = 142). Zones with the highest incidence of vessel strike are highlighted darkest.

Figure 5. Frequency of appearance of injury by body region (n = 149).

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[2] Personal communication from David Rotstein, Marine Mammal Pathology Services, 19117 Bloomfield Road, Olney, MD 20832, September 2014.

[3] Personal communication from Todd Nickerson, Special Agent, NOAA NMFS Northeast Region Office of Law Enforcement, 53 N 6th Street, New Bedford, MA 02740, September 2014.

[4] Personal communication from David Slocum, Operations Coordinator, Stellwagen Bank National Marine Sanctuary, 175 Edward Foster Road, Scituate, MA 02066, August 2015.

Table 1. Definition of healing states.

Phase of wound healing	Physical appearance description	Physiological description
“Fresh/Recent” = Inflammatory Phase	Wound site is often deep red or variations of pink in color. Blubber or muscle layers may be exposed.	Blood clot is formed; blood vessels dilate to allow for antibodies, white blood cells, and nutrients to reach the wound. Autolysing of necrotic tissue (Leaper and Harding 1998).

"Healing" = Proliferation and Maturation phases[a]	Growth band of new tissue begins to form and grow inwards from the edges of the wound site, pigment ranging from variations of pink to white/gray. Later stages of healing may present "normal" pigmentation of the skin matching the uninjured regions; however the shape of the wounded site may continue to evolve.	Proliferation: Wound is "rebuilt" with new granulation tissue combined of collagen and extracellular matrix. The color and condition of the tissue is an indicator of healing (Leaper and Harding 1998). Maturation: The final phase in healing occurs once the wound has closed. Collagen is remodeled and realigned along tension lines where the wound is contracting. This phase can last a year or longer depending on the size of the wound (Mercandetti and Cohen 2005).
"Healed"	Raised or indented ranging from black to white in color (Robbins 2012); stretched, smooth and glossy tissue in appearance (Bloom and Jager 1994, Rommel *et al.* 2007). Appearance of the wound site has remained unchanged over a consistent period of time.	Postmaturation.

[a] Wound healing is a complex process and can be divided three stages: an inflammatory reaction, a proliferative process leading to tissue restoration, then tissue remodeling (Li *et al.* 2007). For the purposes of coding healing stages, no differentiation was made between the proliferation and remodeling phases of healing; both phases were categorized as "healing."

Supporting Information

The following supporting information is available for this article online:

Appendix S1. Case study: NA8988 "Rapier's 2009 Calf."

Figure S1. 10 June 2009; state of healing: Fresh.

Figure S2. 25 June 2009; state of healing: Healing.

Figure S3. 14 July 2009; state of healing: Healing.

Figure S4. 28 September 2010; state of healing: Healing.

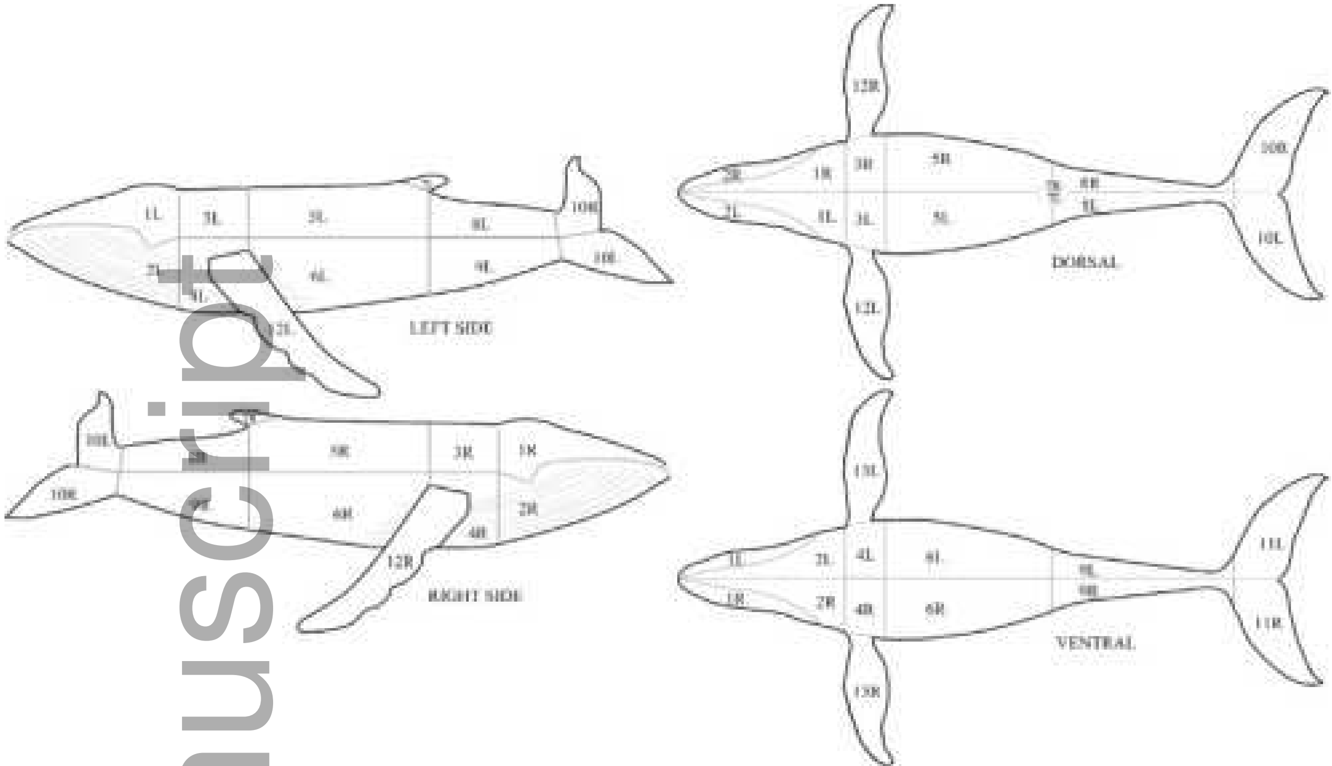
Figure S5. 20 July 2011; state of healing: Healing.

Figure S6. 16 August 2011; state of healing: Healing.

Figure S7. 27 May 2012; state of healing: Healing.

Figure S8. 9 September 2012; state of healing: Healing.

Figure S9. 11 May 2013; state of healing: Healing.



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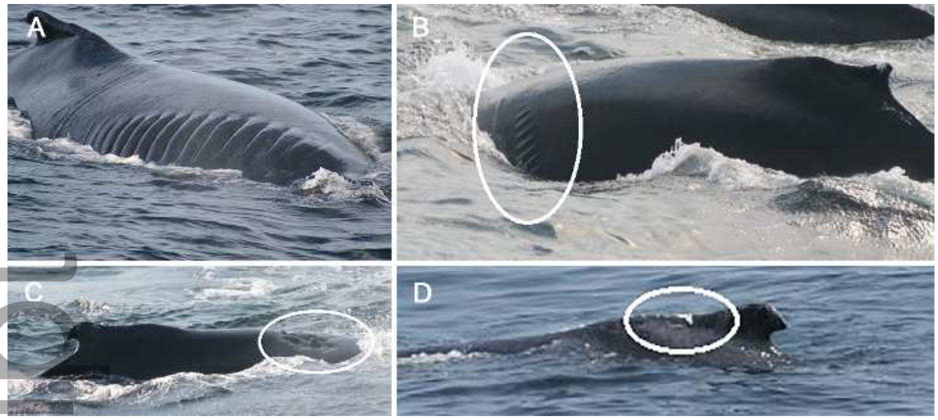

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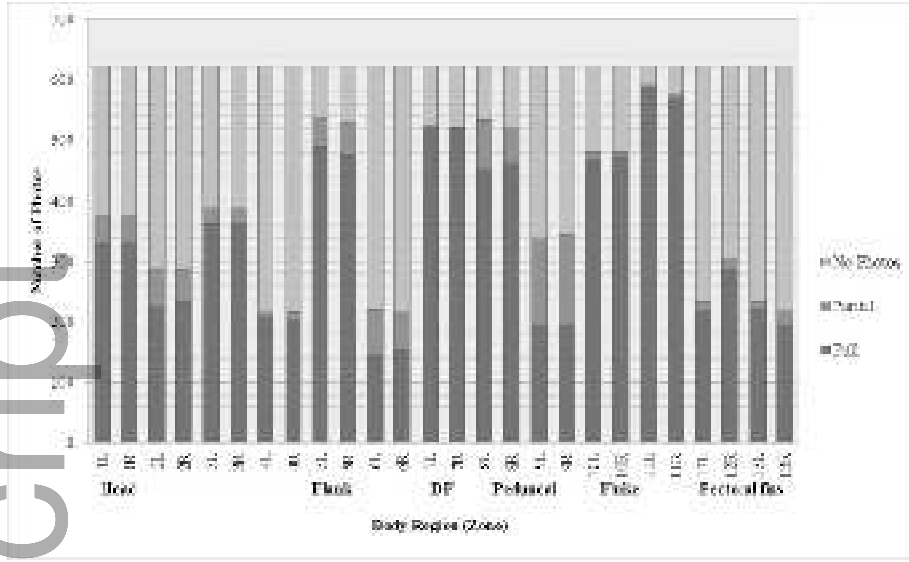

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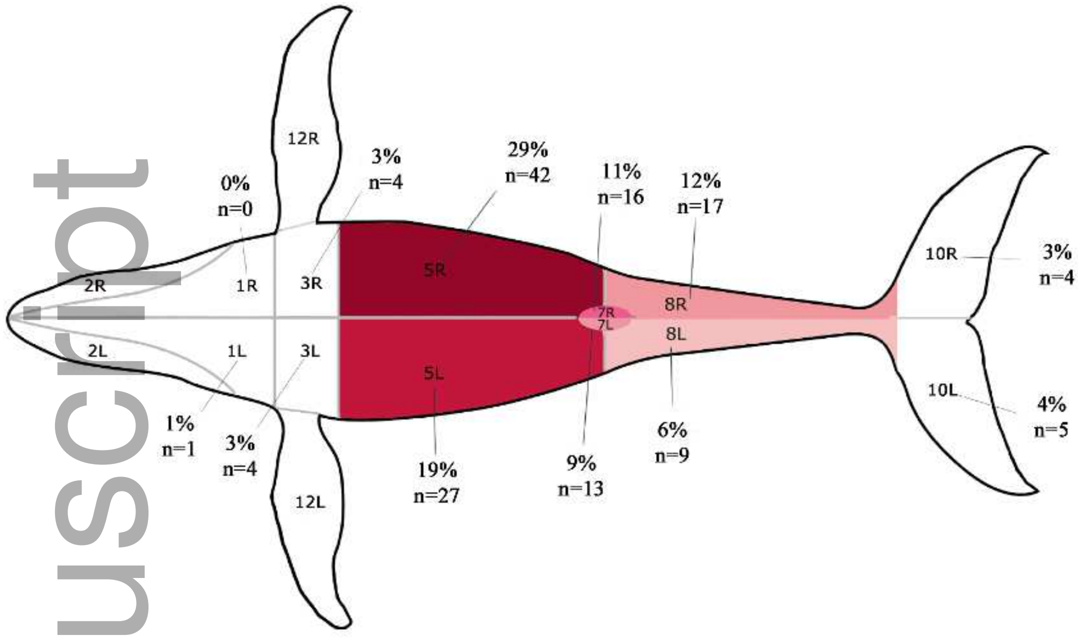

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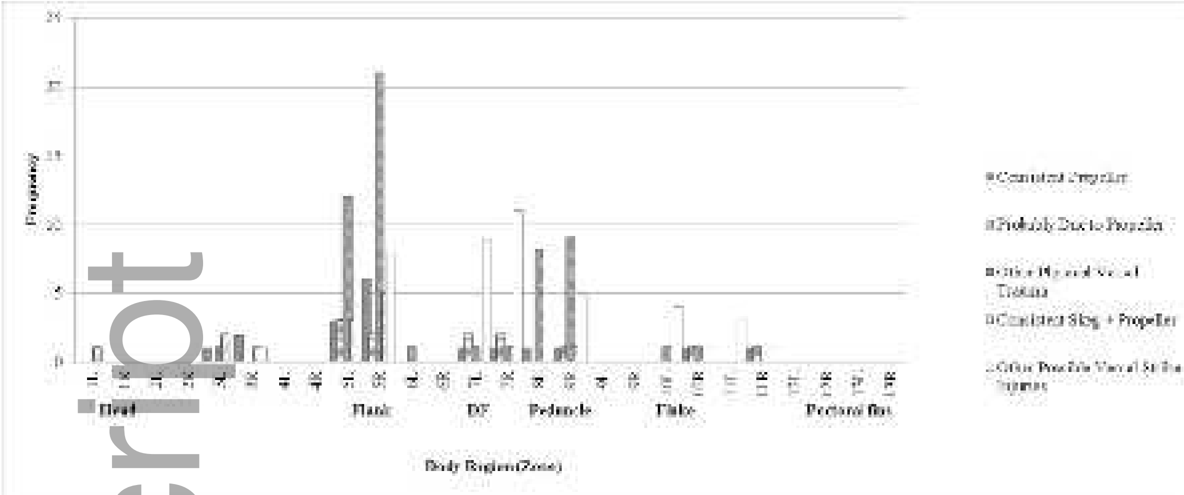

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