



Effects of fishing rope strength on the severity of large whale entanglements

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Abstract: Entanglement in fixed fishing gear affects whales worldwide. In the United States, deaths of North Atlantic right (*Eubalaena glacialis*) and humpback whales (*Megaptera novaeangliae*) have exceeded management limits for decades. We examined live and dead whales entangled in fishing gear along the U.S. East Coast and the Canadian Maritimes from 1994 to 2010. We recorded whale species, age, and injury severity and determined rope polymer type, breaking strength, and diameter of the fishing gear. For the 132 retrieved ropes from 70 cases, tested breaking strength range was 0.80–39.63 kN (kiloNewtons) and the mean was 11.64 kN (SD 8.29), which is 26% lower than strength at manufacture (range 2.89–53.38 kN, mean = 15.70 kN [9.89]). Median rope diameter was 9.5 mm. Right and humpback whales were found in ropes with significantly stronger breaking strengths at time of manufacture than minke whales (*Balaenoptera acuturostrata*) (19.30, 17.13, and 10.47 mean kN, respectively). Adult right whales were found in stronger ropes (mean 34.09 kN) than juvenile right whales (mean 15.33 kN) and than all humpback whale age classes (mean 17.37 kN). For right whales, severity of injuries increased since the mid 1980s, possibly due to changes in rope manufacturing in the mid 1990s that resulted in production of stronger ropes at the same diameter. Our results suggest that broad adoption of ropes with breaking strengths of ≤ 7.56 kN (≤ 1700 lbf) could reduce the number of life-threatening entanglements for large whales by at least 72%, and yet could provide sufficient strength to withstand the routine forces involved in many fishing operations. A reduction of this magnitude would achieve nearly all the mitigation legally required for U.S. stocks of North Atlantic right and humpback whales. Ropes with reduced breaking strength should be developed and tested to determine the feasibility of their use in a variety of fisheries.

Keywords: bycatch, humpback whales, injury severity, North Atlantic right whales, rope diameter, rope manufacturing

Los Efectos de la Resistencia de la Cuerda para Pescar sobre la Severidad de los Enredos de Ballenas Grandes

Resumen: Los enredos en artes de pesca fijas afectan a las ballenas a nivel mundial. En los Estados Unidos, la muerte de las ballenas francas del Atlántico norte (*Eubalaena glacialis*) y de las ballenas jorobadas (*Megaptera novaeangliae*) ha excedido los límites de manejo durante décadas. Examinamos a ballenas vivas y muertas enredadas en herramientas de pesca a lo largo de la costa este de los EUA y las provincias marítimas de Canadá desde 1994 y hasta 2010. Registramos la especie, edad y la severidad de la lesión de las ballenas y determinamos el tipo de polímero de la cuerda, la fuerza de rompimiento y el diámetro de la herramienta de pesca. Para las 132 cuerdas recuperadas de 70 casos, el rango de la fuerza de rompimiento evaluada fue de 0.80–39.63 kN (kiloneutons) y la media fue 11.64 kN (DS 8.29), que es 26% más baja que la fuerza en manufactura (rango 2.89–53.38 kN, media = 15.70 kN [9.89]). La media para el diámetro de la cuerda fue de 9.5 mm. Ambas especies de ballenas fueron halladas en cuerdas con fuerzas de rompimiento en

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manufactura significativamente mayores que las ballenas minke (*Balaenoptera acuturostrata*) (19.30, 17.13, y 10.47 media de kN, respectivamente). Las ballenas francas adultas fueron balladas en cuerdas más fuertes (media 34.09 kN) que las juveniles (medias 15.33 kN) y que todas las clases de edad de las ballenas jorobadas (media 17.37 kN). Para las ballenas francas, la severidad de las lesiones incrementó desde mediados de la década de 1980, posiblemente debido a los cambios en la manufactura de las cuerdas a mediados de la década de 1990, que resultaron en cuerdas más fuertes con el mismo diámetro. Nuestros resultados sugieren que una adopción generalizada de cuerdas con fuerzas de rompimiento de ≤ 7.56 kN (≤ 1700 lbsf) podría reducir el número de enredos que ponen en riesgo la vida de las ballenas grandes en por lo menos 72% y todavía podría proporcionar la fuerza suficiente para resistir las fuerzas rutinarias involucradas en muchas operaciones de pesca. Una reducción de esta magnitud lograría casi toda la mitigación legalmente requerida para los stocks estadounidenses de ballenas francas del Atlántico norte y de ballenas jorobadas. Las cuerdas con fuerzas de rompimiento reducidas deberían ser desarrolladas y probadas para determinar la viabilidad de su uso en una variedad de pescas.

Palabras Clave: ballenas francas del Atlántico norte, ballenas jorobadas, captura accidental, diámetro de cuerda, manufactura de cuerda, severidad de lesión

Introduction

Baleen whales are long-lived species with low reproductive rates that suffered dramatic population declines as a result of historical whaling (Rocha et al. 2014). Ongoing threats to these species have been difficult to assess but include entanglement in fishing gear. Whales play a critical role in ocean ecosystems by enhancing primary productivity in surface and nutrient-poor waters, providing habitat for deep-sea species when carcasses fall to the sea floor, and fixing carbon through these 2 processes (Roman et al. 2014). They also support a whale-watching industry valued at some \$2 billion annually (O'Connor et al. 2009). Understanding anthropogenic effects on whales is essential for whale conservation and has social and ecological ramifications.

Serious injury and mortality from entanglement in fixed fishing gear is a chronic problem facing baleen whales worldwide (Read 2008; International Whaling Commission 2010). Entanglements can lead to near-instantaneous death through drowning (Moore et al. 2013), delayed death from impaired feeding, severe injuries, increased energetic demands when gear remains attached to an individual (Cassoff et al. 2011; Moore et al. 2013), or a stress response that may affect health and fecundity even after the gear is no longer attached (Pettis et al. 2004). The frequency and severity of entanglements have been well studied in endangered North Atlantic right whales (*Eubalaena glacialis*) and humpback whales (*Megaptera novaeangliae*) along the East Coast of North America. For these species, which can reach a length of 16 m, on average 12–16% of the population encounter gear per year (Knowlton et al. 2012; Robbins 2012). For right whales, 83% of the population shows scarring from fishing gear, and the rate of serious entanglement detected over 30 years has increased significantly (Knowlton et al. 2012). Negative effects of entanglement on survival have been documented (Robbins et al. 2015), and observed deaths have exceeded

the potential biological removal (PBR) levels defined by the U.S. National Marine Fisheries Service (Wade 1998) for nearly two decades (van der Hoop et al. 2013; Pace et al. 2014). Federal law in the United States requires substantial reduction in the number of human-caused deaths of both species, including from entanglement.

On the East Coast of the United States, right, humpback, and fin whales (*Balaenoptera physalus*) are protected under the Marine Mammal Protection Act and the Endangered Species Act. In Canada North Atlantic right whales are considered endangered under the Species at Risk Act. As a result of these laws, considerable effort has been directed at documenting entanglement levels, disentangling whales in U.S. and Canadian waters, and collecting and assessing entangling gear. Ropes from a wide range of fisheries have been implicated in entanglements, a majority of which have been identified coming from pot or trap and gillnet fisheries (Johnson et al. 2005). Mitigation efforts in Atlantic U.S. waters include inserting weak links in ropes at certain points and seasonal closure areas for trap and gillnet fishing along the eastern seaboard (van der Hoop 2013). The efficacy of these mitigation efforts remain unknown, partly because ropes are not marked adequately to identify fisheries or locations; how and where entanglements occur is often unknown; and the link between gear characteristics and outcome for whales is poorly understood. Nevertheless, none of these management efforts have reduced serious or lethal entanglements of large whales (Knowlton et al. 2012; van der Hoop 2013; Pace et al. 2014). Recent mitigation efforts have focused on reducing the amount of rope in the water column, either by sinking groundlines between lobster traps or by requiring fisherman to use more traps per vertical “buoy” line. However, it is too early to determine whether these rope reduction methods have been effective as implemented (NMFS 2008; 2014). Studies of retrieved gear samples can offer insights into the causes of entanglement, as well as potential mitigating strategies. Previous studies of entangling gear have focused

on identifying the gear type and components involved in entanglement events (Johnson et al. 2005). Here, we examined additional characteristics of rope retrieved from entanglement events, the configuration of those entanglements, and the resulting injuries to individual whales. Our objectives were to analyze the properties of ropes removed from entangled whales; examine rope characteristics relative to whale species, age, and injury severity; and identify temporal trends in right whale entanglement configurations and injury severity from 1980 to 2009 relative to changes in rope manufacturing practices.

Methods

The Atlantic Large Whale Disentanglement Network recovered most of the gear samples we examined. The samples were removed from free-swimming or anchored entangled whales under the authority of the U.S. National Marine Fisheries Service (NMFS) and Canada's Department of Fisheries and Oceans. They included gear retrieved from right, humpback, and fin whales from Florida to the Bay of Fundy. We augmented these samples with gear from entangled carcasses (including minke whales [*Balaenoptera acuturostrata*], which can reach 9 m in length) on the beach or at sea. All retrieved gear was archived by NMFS. Entanglement configuration was assessed from photographic and written records of the original entanglement event, disentanglement efforts, and stranding records archived at the New England Aquarium (Boston, MA, USA) for right whales, the Center for Coastal Studies (Provincetown, MA, USA) for humpback and right whales, and NMFS for minke and fin whales. Entangled right and humpback whales were identified using photo-identification catalogs maintained by the New England Aquarium and the Center for Coastal Studies, respectively.

Analysis of Ropes

Gear collected from 70 entanglements of large whales from 1994 to 2010 included 132 different ropes. We conducted analyses on samples of the gear to assess the following rope characteristics: diameter (exact measurements and the nearest nominal fraction), material and fiber type (as determined from visual inspection), condition (5 categories: very good, good, fair, poor, very poor, as determined from visual and tactile inspection by experienced analyst H.A.M.), estimated breaking strength, and strength of new rope of the same type and diameter. We used 1 of 3 methods to estimate breaking strength. First, depending on available length, up to 3 3-m specimens of whole rope were pulled to breaking in a laboratory where whole rope strength is tested professionally. Second, all strands were tested for strength with textile testing equipment and rope strength was calculated based on the sum

of the strand strengths multiplied by a realization factor that was based on historical data for rope of a similar size. Third, known breaking strength of a new rope of identical type and diameter was adjusted based on the condition of the entanglement rope. Strength adjustments were 100%, 80%, 60%, 40%, and 20% of new rope strength based on the 5 condition categories from very good to very poor, respectively. Values for the strength-of-new-rope characteristic were selected by H.A.M. based on 11 ropemakers' published data and Cordage Institute standards.

Additional rope characteristics were measured but not analyzed. Complete data and detailed descriptions of methods used for rope analyses are in Supporting Information.

Analysis of Entangled Whales

We combined available life history information, the configuration of gear on the animal, an assessment of injury severity, and data on the rope removed (see example in Supporting Information and <http://www.bycatch.org/research-projects/fishery-animal-interactions> for right whale case studies). In many cases, entanglement configuration and injury severity were reconstructed only from photographs, which limited the detail of some assessments, particularly for humpback whales, because key body parts could not be consistently observed. Less information was typically available for entanglements of fin and minke whales.

Rope diameter and breaking strength at manufacture (i.e., new) were analyzed in relation to whale species, age (or age class), and the severity of entanglement configuration and associated injuries (see below). In some cases entanglements involved more than one rope type, indicating either that multiple components of a gear set were involved or that the whale was entangled in gear from different sets. We used the rope sample with the greatest strength at manufacture and made no attempt to link specific rope samples to specific injuries because entanglements act on whales in complex ways. Descriptive statistics (mean, median, quartile, minimum, maximum, and range) were calculated for breaking strength by species, by injury severity, and by age or age class. For right whales, all individuals were previously catalogued, and the year of birth was known in most cases. We tested statistical differences in the average breaking strength of gear with a one-tailed Student's *t* test ($\alpha=0.05$). The objective was to test the null hypotheses that whale age (a proxy for size, which could not be reliably measured) is not correlated with rope strength; injury severity is unrelated to rope strength; and the severity of right whale entanglement configuration and injuries does not change over time.

Age was determined for right whales based on photographic histories (Hamilton et al. 1998) as calf or juvenile (0–2 years), younger juvenile (3–5 years), older juvenile

(6–8 years), adult (≥ 9 years), or unknown (birth year unknown and sighting history < 8 years).

Humpback whales were allocated to age classes based on known age, sighting history, length, or apparent size as estimated by observers (in the absence of other information). Age classes were juvenile (< 5 years or reported to be of juvenile size), adult (≥ 5 years or reported to be of adult size), and unknown (unknown age and physical size not noted). For minke and fin whales, age and age class were not determined.

We assessed the severity of entanglement injuries for all right and humpback whale cases in which gear was retrieved and analyzed. Minor injuries were superficial skin abrasions, moderate injuries were extensive skin abrasions or cuts that extended into the blubber, and severe injuries were cuts > 8 cm deep or that extended into muscle or bone (Supporting Information). For an injury to be attributed to entanglement, we required evidence of the rope having wrapped at least one body region. Five body regions were assessed for injuries when they were adequately documented: head or rostrum, mouth, body, flippers, and tail. Photographs were not always available of all body parts in contact with fishing gear. When a clear assessment of the injuries could not be adequately made, the case was labeled unknown.

Entanglement duration was also estimated for right and humpback whale cases. Minimum duration was the time between the first sighting of entanglement and the date the gear was retrieved or last sighted on the whale. Maximum duration was the longest time the whale could have been carrying the gear based on the last sighting pre-entanglement without gear and the first sighting post-entanglement where the gear was observed to be gone or the whale was disentangled. For cases in which this information was unavailable, we assumed the minimum duration was 1 day and the maximum duration was unknown. We then identified cases that were known to be short term (maximum duration < 30 days) or long term (minimum duration > 90 days).

Knowlton et al. (2012) showed that the proportion of annually sighted right whales with attached gear or severe injuries increased from 1980 to 2009. To further assess when these changes occurred, 1032 unique entanglement interactions documented from 1980 to 2009 (Knowlton et al. 2012) were scored for injury severity as described above. We performed a binary logistic regression to test the null hypothesis of no change in probability over time ($\beta_1 = 0$), which was assessed using chi-square statistics for the model. We then used an incremental approach to build the data set by each additional year for the logistic model to identify years in which there was significant variation in the probability of moderate or severe entanglements.

We also evaluated changes in the entanglement configuration risk for 73 right whales observed with attached gear from 1980 to 2009. Configuration risk is a measure

of the amount and complexity of entangling gear on the whale and was coded as high or low (Supporting Information). High risk cases involved one or more of the following: one tight wrap, multiple contact points with the gear (attachment points: rostrum or mouth, flipper, body, or tail), or trailing gear longer than one body length or that appeared to substantially impair or prevent movement. High risk cases were considered potentially life threatening. Low risk cases involved no tight wraps, only one attachment point, trailing gear less than one body length, and no heavy gear attached, and were not considered life threatening.

Results

Entangling Rope Characteristics

Rope specimens ($n = 132$) retrieved from 70 entangled whales (30 right, 30 humpback, 8 minke, and 2 fins) consisted of 8 materials (Table 1). The ropes spanned the full range of diameters used in pot and gillnet fishing in the study area, and most (71%) had diameters of 7.9, 9.5, or 11.1 mm (5/16, 3/8, or 7/16 in), diameters commonly used in lobster fishing off the northeast coast of the United States (McCarron & Tetreault 2012). Fifty-three percent ($n = 37$) of the whales with retrieved gear had more than one rope recovered. On average, there were 1.83 ropes analyzed per case (maximum 6 ropes). Although 74% were 11.1 mm (7/16 in) diameter or less, if only the strongest ropes from each entanglement are counted, this percentage dropped to 66%, with an increasing percentage of ropes with a diameter of 12.7 mm ($\frac{1}{2}$ in) or greater (34%) (Table 2).

For rope condition, the majority (70%) were categorized as good to very good (Table 1). Poor or very poor ropes were polypropylene or a polypropylene blend, whereas the others had a wider variety of rope polymers. Rope diameters ranged from 4.7 mm (sold as 3/16 in commercially) to 23.7 mm (1 in), and breaking strengths at manufacture ranged from 2.89 to 53.38 kN, depending on the polymer and diameter (mean[SD] = 15.70 kN [9.89], median = 11.57 kN) (Table 2). The estimated breaking strengths ranged from 0.80 to 39.63 kN (mean = 11.64 kN [8.29], median = 8.90 kN) (Table 2), which is 26% lower than strength at manufacture. (See Supporting Information for figures in lbf and inches.)

Effects of Rope Characteristics on Entanglement

Ropes that entangled right whales ($n = 30$) had higher breaking strengths than ropes that entangled minke whales ($n = 8$; $t = 3.04$, $df = 24$, $P = 0.002$), and ropes that entangled humpback whales ($n = 30$) were of higher breaking strength than ropes that entangled minke whales ($n = 8$; $t = 2.26$, $df = 25$, $P = 0.016$). Ropes that

Table 1. Rope polymer type, range of new and estimated breaking strength, diameter range, and number and apparent condition of ropes removed from entangled large whales off the eastern United States and Canada.

Polymer type	Breaking strength range: new/ estimated; kN (lbsf)	Diameter range: mm (in)	Condition					Total number of ropes (% of total)
			Very poor	Poor	Fair	Good	Very good	
Polypropylene	2.89-53.38/0.80-33.98 (650-12,000/180-7,639)	4.5-23.7 (0.18-0.93)	4	6	8	18	18	54 (41)
Polypro/PET	8.45-30.25/3.11-24.20 (1,900-6,800/700-5,440)	7.9-16.6 (0.31-0.65)	3	6	3	14	8	34 (26)
Polysteel	11.12-51.15/3.36-37.33 (2,500-11,500/756-8,392)	7.8-17.4 (0.31-0.69)	1	1	5	13	6	26 (20)
Polysteel/PET	10.68-19.13/6.77-12.13 (2,400-4,300/1,522-2,727)	7.7-10.6 (0.30-0.42)			1	4	2	7 (5)
Polypro/PET/Lead	7.56-8.90/7.56-8.90 (1,700-2,000/1,700-2,000)	8.5-10.4 (0.34-0.41)					5	5 (4)
Polysteel/Lead	11.12-51.15/6.27-39.04 (2,500-11,500/1,410-8,776)	8.6-20.0 (0.34-0.79)				1	2	3 (2)
Nylon	39.63/23.78-39.63 (8,910/5,346-8,910)	15.7-16.2 (0.62-0.64)			1		1	2 (2)
Polypro/Lead	7.56/6.05 (1,700/1,360)	0.32 (8.2)				1		1 (1)
Total no. of ropes (% of total)			8 (6)	13 (10)	18 (14)	51 (39)	42 (31)	132

Table 2. Summary of diameter and breaking strength ranges of all ropes and the strongest ropes removed from large whales off the eastern United States and Canada.

Range of measured rope diameters (mm, in)	Rope diameter: mm, in (nominal diameter in inches ^a)	Number of ropes (% of total) retrieved from 70 large whales	Number of strongest ropes (% of total) retrieved for each case	New breaking strength range kN, lbsf	Estimated breaking strength range kN, lbsf
4.5-4.7, 0.18-0.19	4.8, 0.19 (3/16)	2 (<2)	2 (<3)	2.89, 650	0.80-1.32, 180-297
6.4, 0.25	6.3, 0.25 (1/4)	1 (<1)	0 (0)	5.03, 1,130	4.02, 904
7.3-8.6, 0.29-0.34	7.9, 0.31 (5/16)	36 (27)	15 (21)	7.56-11.59, 1,700-2,600	1.51-12.27, 340-2,759
8.8-10.3, 0.35-0.41	9.5, 0.38 (3/8)	40 (30)	22 (31)	8.90-15.12, 2,000-3,400	2.16-13.68, 486-3,075
10.3-11.4, 0.41-0.45	11.1, 0.44 (7/16)	18 (14)	7 (10)	8.90-22.24, 2,000-5,000	3.11-19.28, 700-4,335
11.9-13.0, 0.47-0.51	12.7, 0.50 (1/2)	9 (7)	5 (7)	16.81-24.69, 3,780-5,550	4.00-25.09, 900-5,640
13.7-15.0, 0.54-0.59	14.3, 0.56 (9/16)	15 (11)	10 (14)	20.42-31.14, 4,590-7,000	7.03-32.89, 1,580-7,391
15.7-17.4, 0.62-0.69	15.9, 0.63 (5/8)	6 (5)	5 (7)	30.25-40.03, 6,800-9,000	6.05-39.63, 1,360-8,910
19.0-20.0, 0.75-0.79	19.0, 0.75 (3/4)	4 (3)	3 (<5)	33.36-51.15, 7,500-11,500	27.22-39.04, 6,120-8,776
23.7, 0.93	25.4, 1.00 (1)	1 (<1)	1 (<2)	53.38, 12,000	10.68, 2,400

^aNominal rope diameters are those typically used by their manufacturers and lie within or near the range of measured diameters.

entangled right ($n = 30$) and humpback whales ($n = 30$) did not differ significantly ($t = 0.722$, $df = 58$, $P = 0.237$) (Figs. 1 & 2a). The average new rope breaking strength was 19.30 kN (range 7.56-51.15 kN) for 30 right whale

cases, 17.13 kN (range 7.56-53.38 kN) for 30 humpback cases, and 10.47 kN (range 2.89-17.81 kN) for 8 minke cases. For the 2 fin whale cases, the new rope breaking strengths were 11.12 and 31.14 kN.

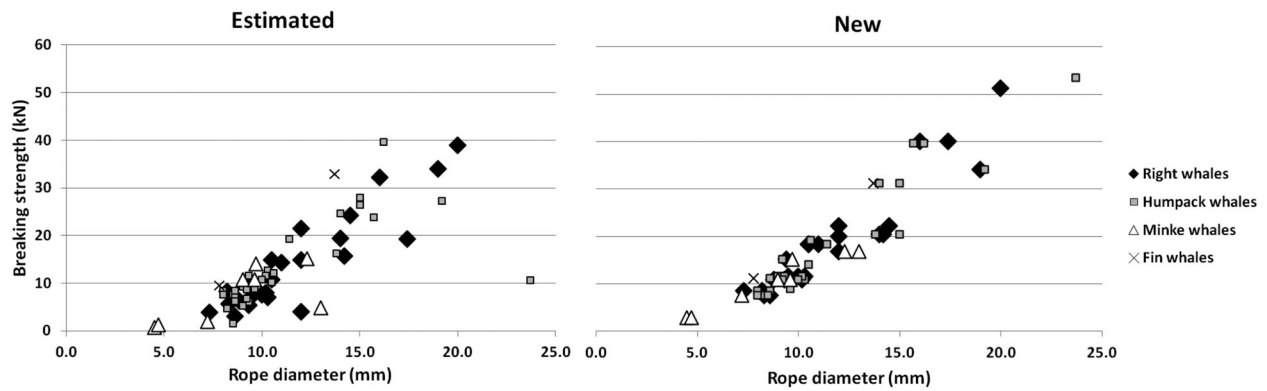


Figure 1. Estimated breaking strength and diameter of all ropes removed from right, humpback, minke, and fin whales (determined by break strength testing or rope condition) and new rope strength and diameter (determined based on strength at manufacture of rope with same polymer make-up and diameter as the rope with the highest breaking strength retrieved from entangled whales).

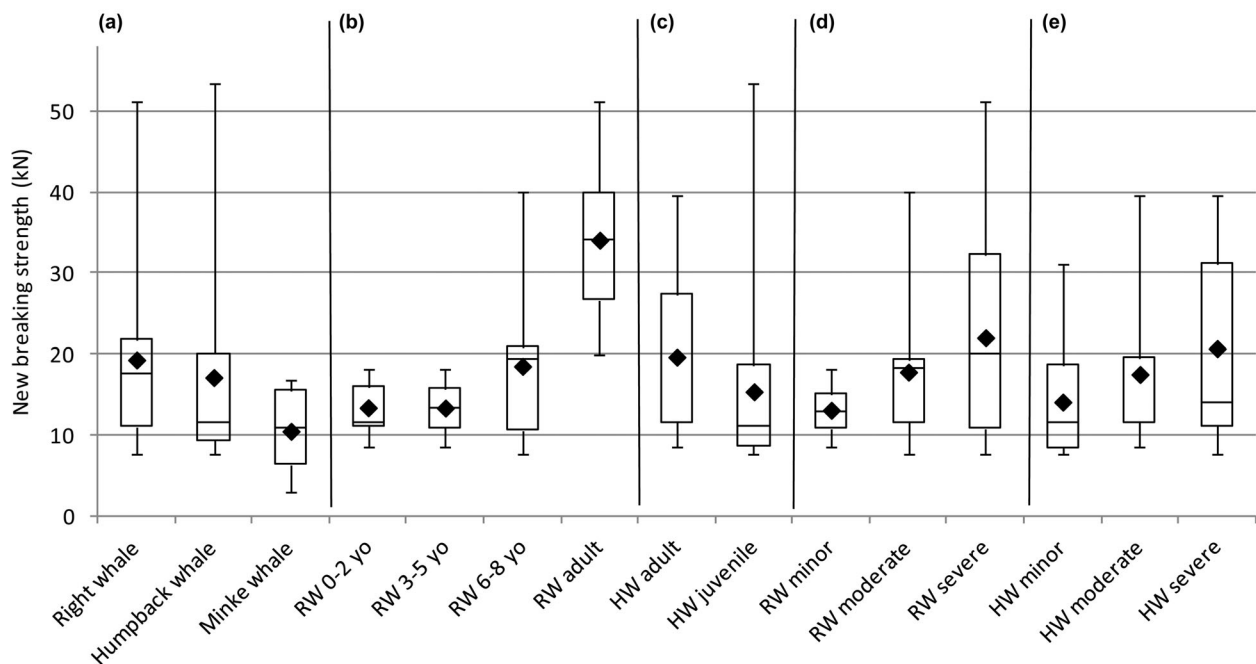


Figure 2. (a)-(e) Relationship between new rope breaking strength and whale entanglement in fishing ropes by (a) species (RW, right whale; HW, humpback; MW, minke), (b, c) age class (yo, years old), and (d, e) severity of injury (bars, middle 50% of measurements collected in each category; line through the bar, median; diamond, mean; whiskers, minimum and maximum breaking strengths documented).

All of the minke whales were found dead in the gear and likely had been anchored (i.e., unable to break free from the gear). Humpback whales were found anchored in the gear in 33% ($n = 9$) of cases, whereas 1 right whale (3.3%) was anchored and subsequently drowned. The anchored right whale was in the strongest gear retrieved for that species (51.15 kN). Breaking strength did not explain why some humpback whales were anchored in gear (average 13.40 kN) and others were not (average 18.60 kN); however, the sample size of anchored whales was low ($n = 9$). Both fin whales were free swimming.

Twenty of the 30 right whale cases (67%) involved calves and juveniles; 7 were adults (23%) and 2 (7%) were of unknown age. Adults were found in ropes of significantly higher breaking strengths than juveniles ($t = 4.26$, $df = 8$, $P = 0.001$) (Fig. 2b & 3c). The case with the highest breaking strength (51.15 kN) involved a male over 19 years old (number 1238) that drowned in the rope (Cassoff et al. 2011).

For humpback whales, 63% ($n = 19$) of the cases involved known or suspected juveniles. Although an adult was entangled in the rope with the highest breaking strength (53.38 kN), both juveniles and adults were

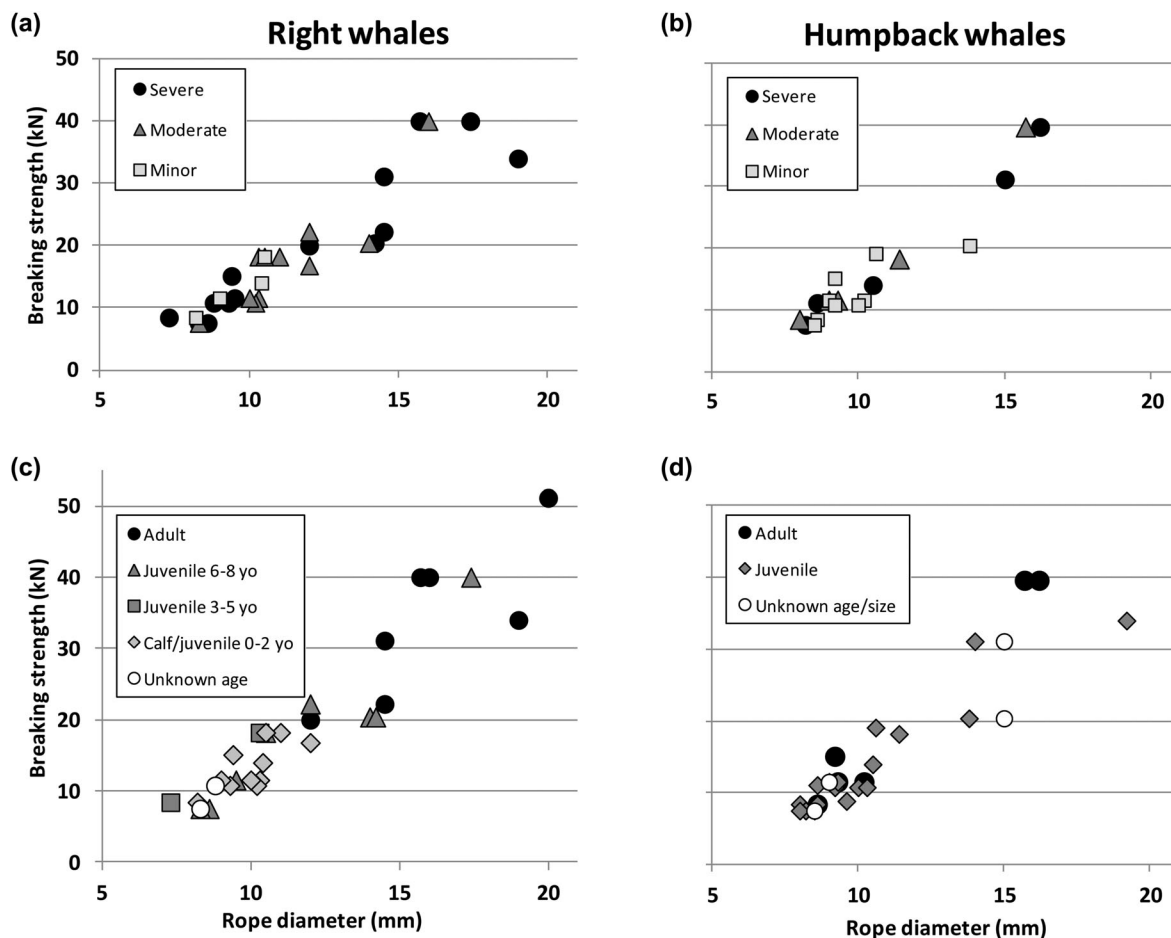


Figure 3. New rope breaking strength and diameter relative to (a) right whale injury severity, (b) humpback whale injury severity, (c) right whale age, and (d) humpback whale age (yo, years old).

distributed across the range of new rope strengths (Fig. 3d), and the average breaking strength did not differ significantly among age classes ($t = 0.576$, $df = 9$, $P = 0.289$) (Fig. 2c). The average breaking strength for adult humpback whales ($n = 7$) was significantly lower than for adult right whales ($n = 7$) ($t = 1.80$, $df = 11$, $P = 0.026$) (Figs. 2b & 2c), whereas juveniles of the 2 species did not differ significantly ($t = 0.319$, $df = 32$, $P = 0.376$).

Entanglement injury severity for 30 cases involving 28 individual right whales (whale number 2212 was entangled 3 times) was predominately severe (50%, $n = 15$); 11 cases (37%) were of moderate severity and 4 cases (13%) were of minor severity (Fig. 3a). This was the only species for which entanglements were confirmed to exceed 90 days ($n = 8$, range: 100–573 days), and all long-term events involved moderate or severe injuries. Although there appeared to be an increasing trend in breaking strengths versus severity (Fig. 2d), these differences were only significant when comparing minor to severe injury cases ($t = 2.155$, $df = 16$, $P = 0.02$).

When entanglement injury severity could be reliably assessed for humpback whales ($n = 20$), the injuries were

most frequently minor (55%, $n = 11$) (moderate, 15%, $n = 3$; severe, 30%, $n = 6$; Fig. 3b). In 10 additional cases, the severity of the injuries could not be reliably assessed. One-third ($n = 10$) of humpback cases were confirmed short-duration events (<30 days), and none were known to be of long duration. The short-duration cases were disentangled within 1–18 days, and the whales exhibited minor to moderate injuries. For the 20 cases with complete information, there were no significant differences in average rope strength for entanglements resulting in minor injuries ($n = 11$) versus those resulting in moderate injuries ($n = 6$; $t = -0.533$, $df = 2$, $P = 0.324$) or severe ones ($n = 5$; $t = 0.999$, $df = 5$, $P = 0.182$) (Fig. 2e).

An overall positive slope parameter ($\beta_1 = 0.046$) indicated an increasing rate of moderate to severe entanglement injury cases in right whales over time ($\chi^2 = 18.467$, $P < 0.001$). Slope parameters differed from those of earlier years in the study, but increases in the rate of moderate to severe entanglement injuries occurred each year from 1997 onward ($\beta_1 = 0.012$, $P = 0.65$) and exhibited statistically significant trends from 2000 onward ($\beta_1 = 0.045$, $P = 0.04$) (Fig. 4a).

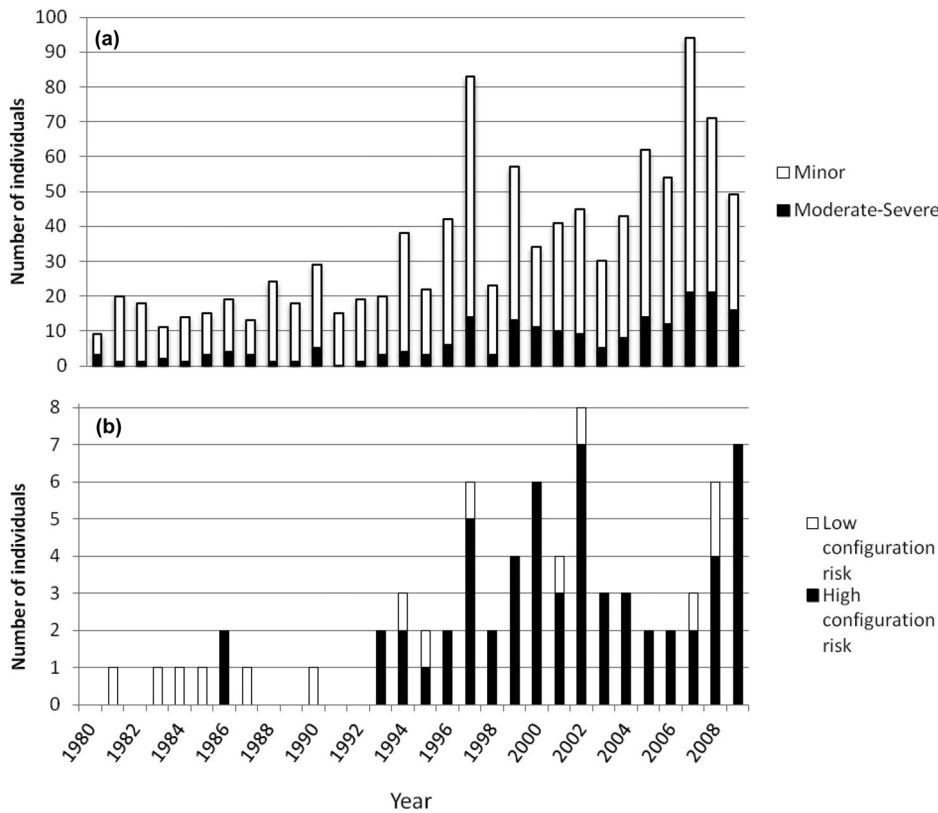


Figure 4. Number of right whales with (a) minor and moderate or severe entanglement injuries and (b) low and high configuration risk entanglements (a measure of the amount and complexity of gear on the whale; high risk cases were considered potentially life threatening) by year.

Entanglement configuration risk was assessed for 73 entangled right whales from 1980 to 2009 (Fig. 4b). During the 1980s and early 1990s entanglements resulting in attached gear were infrequent and typically of low risk. Beginning in 1993, the number of entanglements increased and configuration risk became high for the majority of cases documented through 2009.

Discussion

This is the first study to investigate how rope breaking strength influences entanglement outcome. However, we could rarely determine how the gear was configured when the entanglement occurred or how the whale first encountered the gear. Thus, it is uncertain whether the recovered rope or ropes were the ones initially contacted by the whale. We also do not know if the samples are representative of the strength of the entire gear set. However, we focused on the strongest rope recovered in each case, and we have no reason to believe our sampling was biased in this regard. In addition, the rope strength was somewhere between the new and estimated strength at the time the entanglement occurred. In many of the cases, the whales had carried the gear for extended periods or the retrieved ropes had been stored for several years before analysis. Therefore, we assessed both new and estimated breaking strengths (Fig. 1) and reached the same conclusions. However, we believe the new breaking strength is the most useful metric because most of the

ropes (70%) were in either good or very good condition and therefore would have been closer to new condition at the time of entanglement. Furthermore, metrics based on gear strength at manufacture are easier to incorporate into future mitigation and monitoring efforts.

The null hypothesis that injury severity is unrelated to rope strength was rejected for right whales because the difference in rope strength was significant for minor versus severe entanglement injuries. For humpback whales, an increasing trend in breaking strength versus severity was not significant. These findings may be confounded by several factors. When an entanglement was first detected, entanglement duration was unknown, and injury severity can increase over the duration of an entanglement due to a variety of factors, including infection, amount of drag, and whether the whale grows into constricting gear. Conversely, disentanglement may prevent further injury that might have occurred had the gear remained attached. For example, the greater injury severity in right versus humpback cases may be partially explained by longer entanglement durations. This is related to a number of factors we did not explore, including differences in reporting and disentanglement success rates for the 2 species.

Our second null hypothesis, that rope strength is not correlated with either whale species or age was rejected in several tests. Minke whales, the smallest species, were found in significantly lower breaking strength ropes than both humpback and right whales. When humpback and

right whales were compared by age class, right whale adults were found in significantly stronger ropes than all juvenile right whales as well as both juvenile and adult humpbacks, a species with less girth and strength than rights. The right whale found in the strongest gear (number 1238 in 51.15 kN breaking strength rope) drowned during the entanglement (Cassoff et al. 2011). Further, 0–5 year old right whales were found in rope strengths from 7.56–18.24 kN, whereas adult right whales were found in rope strengths of 20.02–51.15 kN, and 6- to 8-year-olds spanned both ranges. This suggests that either younger right whale juveniles somehow evade entanglement in stronger ropes or that they may be more likely to die in stronger gear and go undetected. This latter scenario is the most plausible given the fact that some whales (including all the minke in this study) were found dead in the gear. In addition, humpback whales were more frequently anchored than right whales, another possible indicator of species strength differences. Finally, the fact that no adult right whales were found in ropes below 20.02 kN suggests they can break free from these weaker ropes and thereby avoid a life threatening entanglement.

Our third null hypothesis that the configuration risk of right whale entanglements and associated injuries do not change over time was rejected in both cases. Injury severity at moderate and severe levels showed a positive slope from 1997 onward, with significant changes beginning in 2000 through the subsequent years covered. Our data suggest the number of entanglements with high configuration risk increased starting in the mid 1990s, and that from 1997 to 2009, high risk configurations represented the vast majority of right whale entanglement cases. All 3 null hypotheses were rejected partially or fully, indicating that breaking strength played a role in entanglement outcome.

Although retrieved rope data were available only for 13 years, information on rope manufacturing might explain this temporal trend. In the early 1950s, fishing rope construction shifted from natural fibers (manila and sisal) to synthetic fibers (primarily polypropylene) that were stronger and resistant to rot. In 1992 the development of co-extrusion (i.e., co-polymer) methods allowed for the blending of different plastic resins to produce stronger and more abrasion-resistant floating ropes (McKenna et al. 2004). A co-extruded rope made of a combination of polypropylene and high-density polyethylene is often referred to by the brand name, *Polysteel*, and is now commonly used for fishing. Another development included the manufacture of sinking ropes composed of a blend of polyester fiber (PET) with either polypropylene or *Polysteel*, which had breaking strengths similar to the all-*Polysteel* ropes (McKenna et al. 2004).

Just prior to rope manufacturing changes in the 1990s, changes in the manufacture of lobster traps also occurred. During the late 1970s and early 1980s, wooden traps were replaced with wire traps that allow for use of

heavier gear, sometimes year round (Fishermen's Voice 2011). The combination of wire traps and stronger, more durable ropes resulted in the ability to fish more and heavier gear in deeper waters and in areas offshore. It seems likely that these changes led to more high risk entanglement configurations and the increased frequencies of moderate and severe injuries for right whales from the mid 1990s onward.

Ours is the first evidence-based analysis that supports a modification to fishing gear that would reduce the incidence of serious whale entanglements in fixed fishing gear. Past mitigation efforts for right and humpback whales were based on common sense and were never subjected to experimental evaluation before or after implementation. We found evidence that reduced breaking strength (RBS) ropes of 7.56 kN (1700 lbf) or less could make a major contribution to whale entanglement mitigation. Based on the limited number of whales found entangled in tested rope strengths below 7.56 kN or 1700 lbf, implementation of RBS ropes would likely reduce the probability of mortality and suffering by at least 72%, assuming such ropes could be practically fished throughout the area covered by this study, and potentially bring entanglement-related deaths to legally mandated levels.

To determine the number of human-caused, deaths that a cetacean species can annually endure without leading to a decline in population size, the United States developed a formulaic approach in which population size, growth, and recovery parameters are used to calculate potential biological removal (PBR) (Wade 1998). The PBR level for right whales is 0.9 whales/year. From 2007 to 2011, entanglement mortality and serious injuries averaged 3.25 whales annually (Waring et al. 2014). For humpback whales, PBR is 2.7 whales but annual mortalities averaged 9.95 whales for the same time frame (Waring et al. 2014). If the broad usage of RBS ropes resulted in the reduction of mortalities and serious injuries by at least 72%, this could reduce annual deaths of right whales to 0.91 and of humpback whales to 2.79, close to the PBR levels set for both species.

The use of RBS ropes would not reduce the number of encounters between whales and gear and may not prevent lethal entanglements in some areas such as the right whale calving grounds, where neonates have less strength than a minke whale. Further, the benefits to other species, such as sea turtles, would likely be minimal. However, the concept of using weaker gear for fishing might be useful to consider in other parts of the world to reduce the capture of small cetaceans or sea turtles. A new study on estimated maximal force output, calculated using measurements of epaxial muscle size of 22 cetacean species ranging from bottlenose dolphins (*Tursiops truncatus*) to blue whales (*Balaenoptera musculus*), may provide valuable insights into the rope or net strength different species can break (Arthur et al. 2015).

The RBS ropes also need to be practical for fishing. Load cell studies in the Gulf of Maine show near shore lobster trawl hauling loads are around 2.24–3.11 kN, except in one instance where it was recorded at 4.89 kN (Salvador & Kenney 2002). However, loads reached 12.46 kN during hauling of very heavy offshore gear (a 48-trap trawl in 185 fathoms) (Salvador et al. 2003). The highest load cell measurement of gillnet gear from the Bay of Fundy was 3.11 kN during setting and 2.45 kN when hauling from gear set in 50 fathoms with an 0.36 kN grapple and 0.38 kN kedge type anchors (Salvador & Kenney 2002). When towed, the drag on an unanchored 20-net string of gillnets reached 6.38 kN (Salvador & Kenney 2002). These studies suggest the forces applied during normal fishing operations are considerably lower in most cases for lighter gear than the 7.56 kN maximum RBS rope we recommend.

Rope used for fishing is stronger than needed under average operating conditions. This gives fishers a margin of security against rope degradation from repeated hauling stress, abrasion, UV exposure, rope age, and to withstand high loads during severe weather, currents, and when ropes become stuck on rocks or in other gear. If RBS ropes were used, the development of a more durable rope might reduce the chances of greater gear loss from using weaker ropes with unchanged degradation resistance. Preliminary trials of RBS ropes of 2.67 and 5.34 kN by lobster fishers in the Gulf of Maine in 2006 and 2007 indicated that the ropes were fishable in some areas and fishers were receptive to the concept (Consortium for Wildlife Bycatch Reduction 2007, 2009). The use of RBS ropes may also reduce the chance that bottom gear would be dragged if the set were snagged by an entangled whale or by a passing vessel and thus provide more accurate positioning of nonbuoyed gear to facilitate retrieval through grappling. Accidental towing of lobster gear by passing vessels is considered one of many reasons gear is lost (Prybot 2006). In areas where RBS ropes may not be feasible for fishing, the development and implementation of other bycatch mitigation techniques such as rope-less fishing should be tested.

These results suggest that the development and implementation of RBS ropes could lead to a significant reduction of whale mortality and serious injury from entanglement in fishing gear. Previous management measures to reduce entanglements of large whales have required weak links between the top of the vertical endline and the surface buoy system of pot and gillnet gear and between gillnet panels. Evidence indicates that these and other measures have not reduced either the incidence or severity of entanglements along the eastern seaboard (Knowlton et al. 2012; Pace et al. 2014). With RBS ropes, the goal would be to make the entire length of the lines in the water column weaker, rather than only at specific points. This would give an entangled whale a better chance of breaking free regardless of where it makes contact with the line.

The RBS ropes should be tested in any part of the world where whale entanglements occur in fixed fishing gear and should be considered for any rope-based marine activity. Short-term evaluation of its efficacy could be determined through gear marking to assess the injury severity and configuration risk for RBS ropes found on whales. Long term efficacy can be determined by monitoring entanglement rates and severity levels in the target population. Considering that entanglement is one of the most urgent conservation issues facing marine mammals, adopting this relatively simple gear modification is a promising option for reducing the number of unnecessary deaths and suffering by whales around the world.

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Supporting Information

Supporting information on methods of rope analyses and associated data (Appendices S1 and S2), a right whale case study example (Appendix S3), entanglement injury and configuration severity criteria (Appendix S4), and figures shown in pounds force and inches (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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