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Predicting lethal entanglements as a consequence of drag from fishing gear

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Abstract (149/150 words)

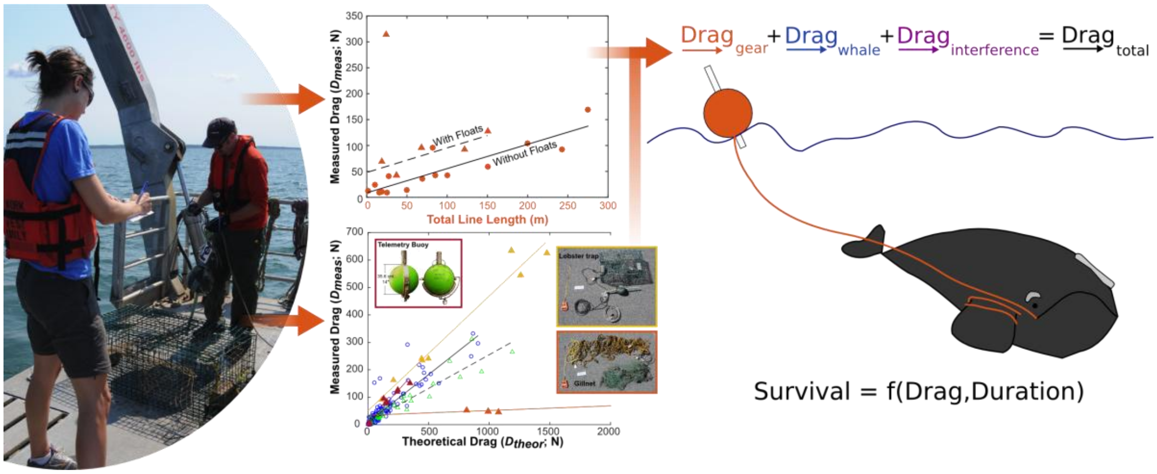
Large whales are frequently entangled in fishing gear and sometimes swim while carrying gear for days to years. Entangled whales are subject to additional drag forces requiring increased thrust power and energy expenditure over time. To classify entanglement cases and aid potential disentanglement efforts, it is useful to know how long an entangled whale might survive, given the unique configurations of the gear they are towing. This study establishes an approach to predict drag forces on fishing gear that entangles whales, and applies this method to ten North Atlantic right whale cases to estimate the resulting increase in energy expenditure and the critical entanglement duration that could lead to death. Estimated gear drag ranged 11-275 N. Most entanglements were resolved before critical entanglement durations (mean±SD 216±260 days) were reached. These estimates can assist real-time development of disentanglement action plans and U.S. Federal Serious Injury assessments required for protected species.

Keywords: drag, right whale, serious injury, body condition, entanglement duration, large whale(s)

Highlights

- Large whales are often entangled in fishing gear for months to years.
- Drag and energy burden from entangling gear can be estimated at the time of a whale's detection.
- We develop tools for prognosis of specific entanglement cases to assist disentanglement action and inform stock assessment.

Graphical abstract



Introduction

Marine animals are frequently entangled in fixed fishing gear (Read et al., 2006; van der Hoop et al., 2013a), with larger whales often able to break free of anchor points. In doing so, some whales are able to continue to swim for days to years while carrying a portion of gear with them. For most large whales, the proximate source of entanglement is actively fished (vs. derelict) gear (Butterworth et al., 2012; Laist, 1997; Lyman, 2012), though the gear is dislodged, leaves the fishery site, and is carried by the animal. Efforts to disentangle large whales in particular have been developed in areas where incidence is especially high (e.g., by the Center for Coastal Studies in Provincetown, MA, U.S.A.) and information and experience gained by the teams involved in these efforts have been shared worldwide as the entanglement issue has been recognized as a global issue (IWC, 2010, 2011).

When entangled whales are reported, depending on the level of information provided at the initial report and the whale's proximity to a response effort, an evaluation is made as to whether the entanglement is likely life threatening. For life threatening cases, trained disentanglement teams develop action plans to determine whether the whale is a candidate for disentanglement, and if so what the response can or should involve (IWC, 2010). The plan considers the specific configuration of the gear on the animal and the animal's apparent health as described by observers or as documented in photographs or video. There is a sense of urgency to remove gear, and a clear set of protocols are implemented to properly assess the case and design a plan that prioritizes both animal and human safety. Depending on the species, environmental conditions, and gear, numerous disentanglement attempts may be required over days to months (Moore et al., 2010).

Entangled whales are subject to considerable drag forces (van der Hoop et al., 2016; van der Hoop et al., 2013b), which demand increased thrust power and therefore energy expenditure over time. Whales can persist with chronic entanglements for years, yet most entangled North Atlantic right whales (hereafter right whales; *Eubalaena glacialis*) die within six months to a year after detection (Moore et al., 2006) if they are not successfully disentangled early on. Health impacts are the most predictive of subsequent survival of entangled right whales (Robbins et al., 2015). Longer entanglement durations are more likely to lead to severe injuries (Knowlton et al., 2016) and the total energy expenditure over the course of entanglement has been linked to individual fate (van der Hoop et al. Accepted Ecol and Evol); the impact of entanglement drag over time is therefore a critical element to consider when developing response action plans or assessing whether an entanglement is life-threatening (IWC, 2010; NOAA, 2008).

How long can entangled right whales survive, given the unique configurations and dimensions of the gear they are towing? While it is possible to measure drag on some sets of gear (e.g., van der Hoop et al., 2016; van der Hoop et al., 2013b), drag forces can also be estimated from well-established physical theory (Faltinsen, 1993; Fridman, 1986; Helmond, 2001; Keith et al., 2004). To determine the relationship between measured and theoretical drag forces, both methods were applied to sets of fishing gear that had entangled or are similar to those entangling right whales. This relationship was then applied to entanglement cases for which drag forces had not been measured, to estimate (a) the drag experienced by these whales, (b) the resulting increase in energy expenditure, and the (c) potential longevity of each individual in its entangled condition.

Methods

Table 1. List of Symbols and Abbreviations

Symbol	**Definition**	**Unit**
α	Incident flow angle	degrees
A_w	Wetted surface area	m^2
C_d	Drag coefficient	
d	Line diameter	m
D	Drag force	N
D_{corr}	Corrected drag force	N
D_f	Drag forces on floats or traps	N
D_I	Interference drag force	N
D_l	Drag forces on line	N
D_{max}	Maximum entanglement duration	days
D_{meas}	Measured drag force	N
D_{min}	Minimum entanglement duration	days
D_{theor}	Theoretical drag force	N
D_{tot}	Entangled whale total drag force	N
D_w	Whale body drag force	N
η	Overall efficiency	
η_m	Metabolic efficiency	
η_p	Propulsive efficiency	
l	Total length	m
P_T	Thrust power	W
ρ	Density	kg/m^3
q	Hydrodynamic stagnation pressure	N
t	Time	s
U	Speed	m/s
V	Total body volume	m^3
W_a	Additional work	J
z	Tow point depth	m

Measured Gear Sets

Hydrodynamic drag forces on 21 sets of fishing gear removed from or similar to those entangling right whales were measured in a previous study *via* tensiometer (Dmeas; van der Hoop et al., 2016). Drag forces on these same gear sets are estimated here from theory (Fridman, 1986). Total length and line diameter were measured from dry gear. All symbols and abbreviations are listed in Table 1.

The drag force on fishing ropes can be estimated by

(1)

where C_d is the drag coefficient, l the total length (not just trailing length; m), and d the diameter (m) of the line, and q is the hydrodynamic stagnation pressure (N):

(2)

where ρ is seawater density (1025 kg/m^3) and U is the relative speed through water (i.e., including currents) at each tow point (~0.77, 1.3, and 2.1 m/s). C_d is estimated from Fridman (1986; Table 3.3) based on the angle between the line and the flow direction α, calculated from the depth of each tow point (z; ~ 0, 3, and 6 m) and the length of the line,

. (3)

Drag from floats, traps or buoys is estimated as

(4)

where A_w is the wetted surface area (m^2) of each rigging component (see Appendix II in van der Hoop et al., 2016) and corresponding C_d values for typical rigging shapes in Fridman (1986; Table 3.5). The total theoretical hydrodynamic drag (D_{theor}) on a gear set is then the sum of the drag forces on the line (D_l) and floats and/or traps (D_f) if present:

. (5)

A linear model was fit to the theoretical (D_{theor}) and measured drag (D_{meas}) values, with float as a categorical covariate. This equation for corrected drag, D_{corr}, was then applied to ten other sets of entangling fishing gear that were not measured, but whose dimensions were sufficiently described to estimate drag forces from theory.

Non-Measured Gear Sets

Ten sets of fishing gear entangling right whales were sufficiently described with dimensions to estimate drag forces from theory following equations 1 through 5. Body length and weight of the ten entangled whales were estimated from age at first entanglement from Moore et al. (2004), and maximum body width from length as in Fortune et al. (2012). These body dimensions were used to estimate drag forces on the whales' bodies, D_w (N), as in van der Hoop et al. (2016; Eq. 8). Similar to the Measured gear sets above, gear dimensions were obtained from gear after it was collected. Total length refers to the length of all of the retrieved gear, rather than the length of trailing line; no effort was made to estimate dimensions of gear that was not removed or not retrieved. As such, all cases are underestimates of the total gear on the whales. Wetted area (A_w) was estimated for all additional gear components (Appendix I). Drag was estimated at 1.23 m/s, the upper 95% CI of satellite-tag derived swimming speeds for right whales (Baumgartner and Mate, 2005; van der Hoop et al., 2012) and at a depth (z) of 0 m. These D_{theor} were then corrected based on the linear relationship established above to yield a corrected drag value D_{corr}, so as to enable direct comparison with the measured drag forces (D_{meas}) from van der Hoop et al. (2016).

Interference drag (D_I, N) from each entangling gear set was estimated based on the location on the body, height, and frontal area at the attachment point (Jacobs, 1934; Eq. 11 in van der Hoop et al., 2016). The number of wraps on different body parts and the dimensions of the gear where it attaches greatly affect the magnitude of interference drag (van der Hoop et al., 2016; van der Hoop et al., 2013b). The total drag on each entangled whale (D_{tot}) was then:

$$D_{tot} = D_w + D_I + D_{corr}\ . \qquad (6)$$

Thrust power requirements to overcome drag for swimming when entangled ($P_{T,e}$; W) and not entangled ($P_{T,n}$; W) were calculated as:

$$\frac{\quad}{\quad} \qquad (7)$$

$$\frac{\quad}{\quad} \qquad (8)$$

where η is the maximum swimming efficiency (i.e., $\eta_m \times \eta_p$; muscular × propulsive) of a right whale when not entangled ($\eta_n = 0.13$) and entangled ($\eta_e = 0.13$) based on van der Hoop et al. (Accepted ESR). Maximum propulsive efficiencies were applied instead of mean values for a more conservative estimate. As the simplest scenario, it was assumed that entanglement did not affect an individual's swimming speed ( ), *i.e.*, that animals do not slow down once entangled.

The additional work (W_a, J) required to swim when entangled was calculated as

$$, \qquad (9)$$

where t is time (in seconds). van der Hoop et al. (Accepted Ecol and Evol) determined the amount of additional work performed by entangled right whales based on their minimum and maximum entanglement durations. Individuals who died performed significantly more work; the 0.75 quantile of minimum additional work performed by whales that did not survive their entanglements was 8.57×10^9 J. This is therefore considered to be the critical level of additional energy expenditure, which if reached, may be fatal. t was increased to determine the time required for these ten whales to reach this critical level of energy expenditure. The expected lethal entanglement durations were compared to the actual, observed minimum and maximum entanglement durations of each whale and were interpreted with disentanglement dates and the known fates of the individuals to determine whether or not energetic costs alone can predict mortality or serious injury in entangled whales.

Entanglement durations were calculated from sightings histories and disentanglement records of each whale (NARWC, 2015). Maximum entanglement durations (d_{max}) were calculated based on the last gear-free sighting before entanglement, and either first confirmed gear-free sighting following disentanglement, death (confirmed by carcass detection and identification), or presumed death (once an individual has not been sighted in 6 years; Knowlton et al., 1994). Minimum entanglement durations (d_{min}) were calculated based on the first entangled sighting and either the date of disentanglement (including partial disentanglement), the date last seen entangled, or the date that a telemetry buoy, if it was attached during disentanglement efforts, ceased transmissions. To show the unique subset of entanglement case data used in this study, the sightings histories and minimum and maximum entanglement durations of the ten Non-Measured cases were compared with the 15 Measured cases and 47 others as described by Knowlton et al. (2015).

Disentanglement Response

Disentanglement response typically focuses on removing all or most of the gear from the whale, but in some cases shortening the length of trailing line to 1 body length is the best option available. To determine the drag reduction and increase in critical entanglement duration achieved in doing so, gear drag was estimated a second time with the length of gear equal to the body length of the entangled whale involved in each case (Table 2) and with floats and buoys removed if they were initially present. For one case (Eg 2151) where the gear was already <1 body length, the length of the gear was not changed.

Sensitivity to Gear Parameters

To determine the sensitivity of the assessment tool, critical durations were estimated for all 10 cases by adding in levels of information. The first estimate included gear length only, then added the gear diameter and then the attachment point. If the entanglement included floats, four estimates were made: (1) the length of the gear with the presence of a float, then adding (2) gear diameter, (3) attachment point and finally (4) the specific dimensions of the float.

Results

Theoretical drag forces (D_{theor}) vary consistently from measured drag values (D_{meas}) at the same depths and speeds (Figures 1, 2). The slopes between measured and theoretical drag are 0.335(±0.161); however, the lobster trap and telemetry buoy have much greater slopes (0.418 and 0.483 respectively), and the gillnet gear has a much lower slope (0.017), than the rest of the measured gear sets (Figure 2). Removing these three sets, measured drag can be predicted from drag estimated with theory, yielding a correction equation (D_{corr}) of:

$$D_{corr} = 8.83 + 0.35 \times D_{theor} - 0.10 \times D_{theor} \times \text{float}, \qquad (10)$$

where float is a binary covariate (RMSE = 27.2, Adj. $R^2 = 0.846$, $p < 0.0001$). A separate relationship was fit to correct for an attached lobster trap ($D_{corr,lobs}$):

$$D_{corr,lobs} = 50.81 + 0.418 \times D_{theor}\text{ , (RMSE = 41.8, Adj. } R^2 = 0.965,\ p < 0.0001) \qquad (11)$$

and the telemetry buoy ($D_{corr,telem}$):

$$D_{corr,telem} = 4.91 + 0.483 \times D_{theor}\text{ , (RMSE = 15.4, Adj. } R^2 = 0.932,\ p < 0.0001) \qquad (12)$$

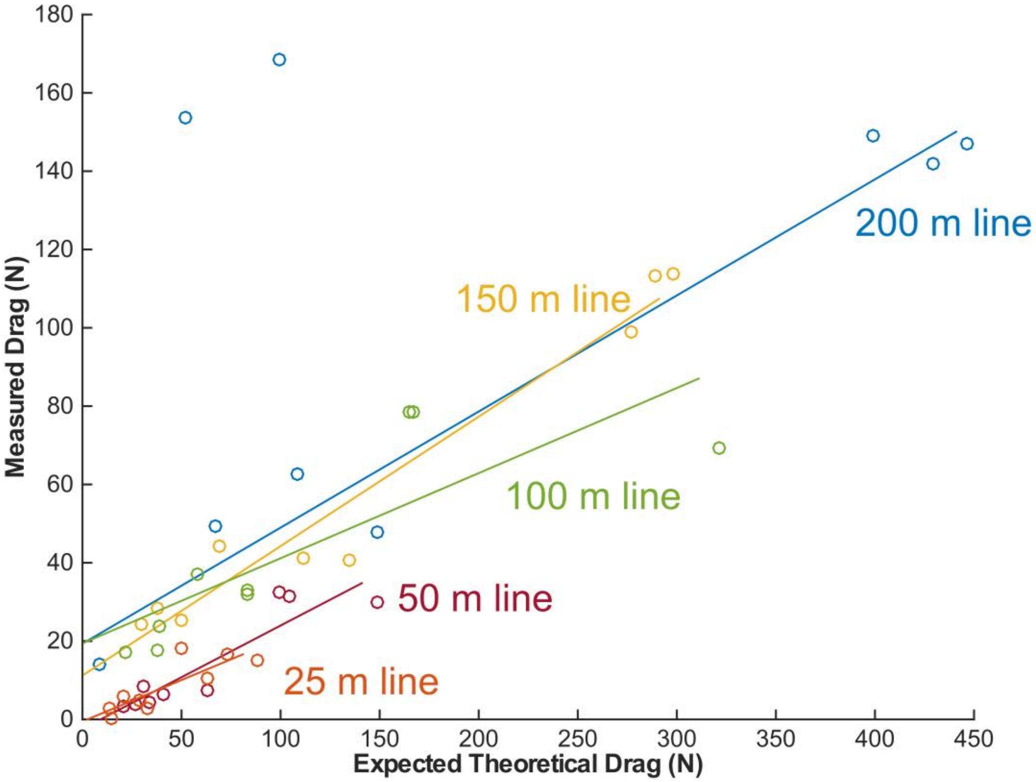


Figure 1. Expected theoretical forces vs. measured drag forces (N) on five lengths of 8 mm diameter polypropylene rope. Colors represent different lengths of line (blue, 200 m; yellow, 150 m; green, 100 m; red, 50 m; orange, 25 m. Each point represents a measurement and estimation at specific depths (~ 0, 3, and 6 m) and speeds (~0.77, 1.3, and 2.1 m/s).

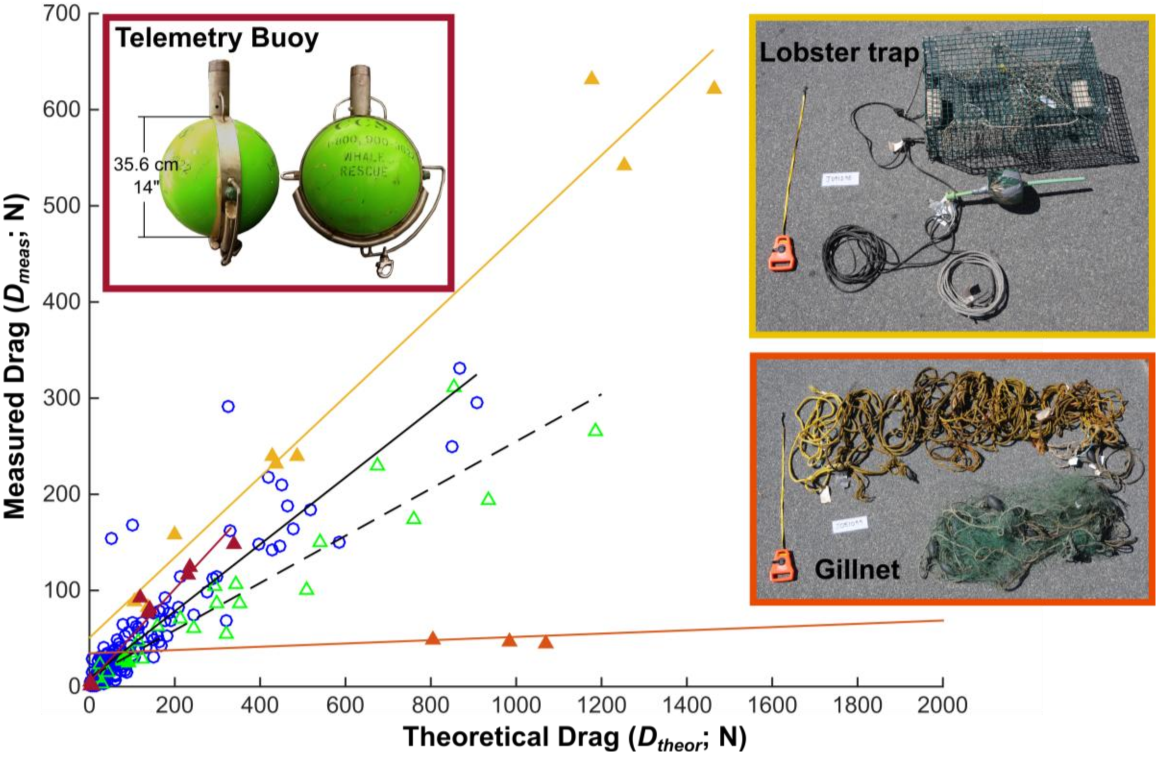


Figure 2. Expected theoretical vs. measured drag forces (N) on 15 sets of fishing gear removed from entangled North Atlantic right whales, the satellite telemetry buoy, and 200, 150, 100, 50 and 25 m of 8 mm diameter polypropylene line. Each point represents a measurement and estimation at specific depths (~ 0, 3, and 6 m) and speeds (~0.77, 1.3, and 2.1 m/s). Blue circles represent gear sets with only line; green triangles represent gear sets with additional floats or buoys; red, yellow, and orange triangles are the telemetry buoy, lobster pot and gill net gear, respectively, which are not used in the linear model fit between measured and theoretical drag for gear sets made up of only line (solid line), or with the presence of floats (dashed line) as a categorical covariate. See text for equations.

Non-Measured Gear Sets

Corrected drag values for the ten sets of gear that were not towed ranged 11.5-281.0 N at 1.23 m/s. These corrected drag values (D_{corr}) were combined with estimated whale drag (D_n) and interference drag (D_I) to yield the total drag estimated for each of the entangled whales swimming at 1.23 m/s (Figure 3A). Total gear drag ($D_{corr} + D_I$) contributed 86.0±94.6% to total body drag, but ranged from 7.6-260% (Figure 3A). Generally, greatest gear drag contributions were seen in entanglements involving the youngest and therefore smallest animals (Eg 3392 = 233%, Eg 3281 = 260%), although some young animals also experienced low gear drag contributions (Eg 3120 = 38.9%, Figure 3A).

To overcome additional drag forces, these entangled whales expended significantly more power ($P_{T,e}$ = 3030±1071 W) compared to when not entangled ($P_{T,n}$ = 1870±923 W; paired *t*-test, t_{18}= 2.5927, p = 0.0184). Over the course of one day swimming at 1.2 m/s, these entangled whales would have to do 1.00×10^{8} J more work (W_a) than they would if not entangled (Figure 3B).

These 10 whales would have reached the critical additional energy requirement of 8.57×10^{9} J in 216±260 days (range 38-914 days; Figure 3C, D), which can be compared to their observed entanglement durations (Figure 3D). One whale's minimum entanglement duration exceeded our critical additional work threshold (Eg 3120), whereas four whales' maximum duration exceeded the threshold (Figure 3D). Only two of the 10 whale cases died, 37 and 815 days before the critical entanglement duration was reached.

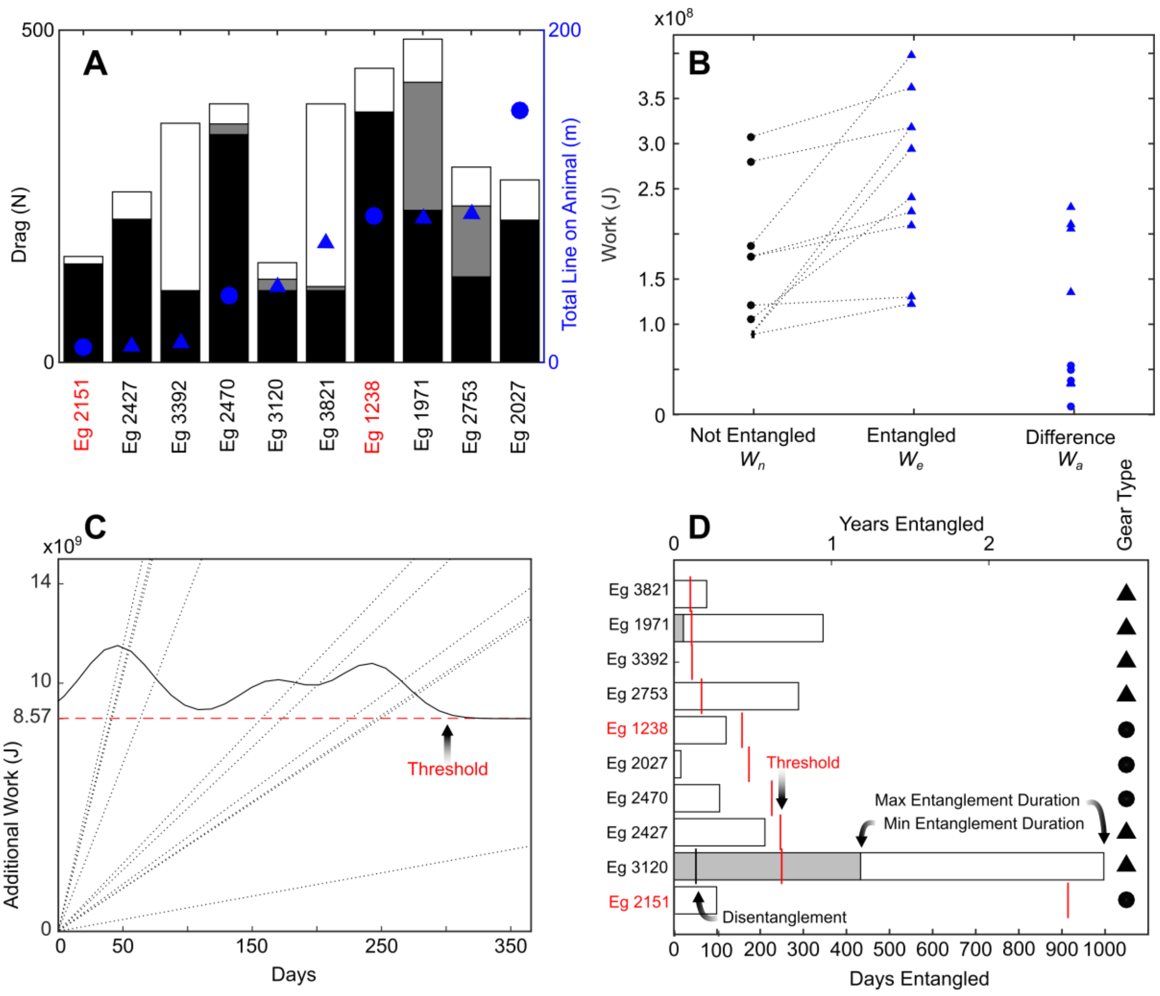


Figure 3. A: Drag forces (N) on the bodies (black) of ten right whales (identified by Eg number), and interference (grey) and measured (white) drag from entangling gear. Red label text indicates whales that died. Blue markers represent the total length of line used in the drag estimate; circles represent gear made up of only line, triangles represent gear with floats or traps. See text for details. **B:** Total work (J) required for ten right whales swimming for one day at 1.23 m/s when not entangled (W_n; black closed symbols) and entangled in fishing gear (W_e; blue closed symbols), as well as the additional work required ($W_a = W_e - W_n$; blue open symbols) when entangled. **C:** Additional work (W_a, J) over increasing entanglement durations for each whale (black dotted lines) to determine the number of days until individuals expend minimum critical additional energy levels (red dashed line). The black line shows the distribution of days until minimum critical additional energy levels are reached. **D:** Minimum (grey) and maximum (white) observed entanglement durations of 10 right whales (Eg numbers) and time until minimum critical levels of additional energy expenditure (red lines) are reached. Red label text indicates whales that died. Black lines represent the day of disentanglement; if not visible, the whale was disentangled on the day of entanglement detection (day zero) except for Egs 1238 and 2151, neither of which were disentangled.

Table 2. Details of fishing gear entanglements whose drag forces were estimated (*n* = 10). Sightings data provided the minimum and maximum entanglement periods (days), individual fate (S = survived; D = died) and age or minimum age at entanglement (years) for all whales, from which length and weight were estimated from Moore et al. (2004).

Catalog Number	**Age at Entanglement (years)**	**Estimated Length (m)**	**Estimated Weight (kg)**	**Entanglement duration (days)**		**Fold increase in Drag**	**Floats**	**Non-entangled Power ($P_{T,n}$, W)**	**Entangled Power ($P_{T,e}$, W)**	**Additional Power ($P_{T,a}$, W)**	**Additional Work (W_a; J)**		**Fate**
				Min	**Max**						**Min**	**Max**	
Eg 1238	20+	14.28	38643	1	121	1.26	0	3558	4188	631	5.45×10^{7}	6.59×10^{9}	D
Eg 1971	8	13.00	17359	22	346	2.28	1	2165	4603	2438	4.63×10^{9}	7.29×10^{10}	S
Eg 2027	7	12.82	15585	1	16	1.37	0	2026	2598	572	4.94×10^{7}	7.91×10^{8}	S
Eg 2151	3	11.64	8490	1	99	1.15	0	1399	1508	109	9.38×10^{6}	9.29×10^{8}	D
Eg 2427	7	12.82	15585	1	211	1.28	1	2026	2428	403	3.48×10^{7}	7.34×10^{9}	S
Eg 2470	17+	14.05	33322	1	106	1.22	0	3244	3682	438	3.79×10^{7}	4.01×10^{9}	S
Eg 2753	2	11.08	6717	1	289	2.45	1	1218	2782	1564	1.35×10^{8}	3.91×10^{10}	S
Eg 3120	1	10.11	4943	433	997	1.49	1	1022	1420	398	1.49×10^{10}	3.43×10^{10}	S
Eg 3392	1+	10.11	4943	1	Unk	3.57	1	1022	3406	2383	2.06×10^{8}	-	S

Eg 3821	1	10.11	4943	1	76	3.86	1	1022	3681	2659	2.30×10^{8}	1.75×10^{10}	S

Disentanglement Response

Partial disentanglements that cut trailing line to 1 body length and remove any floats from these 10 cases would reduce gear drag forces from on average 88.4(±94.2) N (range 11.1-274.9 N) to 13.6(±2.3) N (range 11.1-18.1 N; Fig 4A). Total entangled whale drag would be reduced by 21(±25)% and up to 68% for cases where lobster traps were to be removed (Fig 4B). Additional work required for swimming would be significantly reduced (t_9 = 4.3870, p = 0.0018; Fig 4C) and critical duration would increase significantly by on average 304(±295) days (range 0-824 days; t_9 = 3.2567, p = 0.0099; Fig 4D).

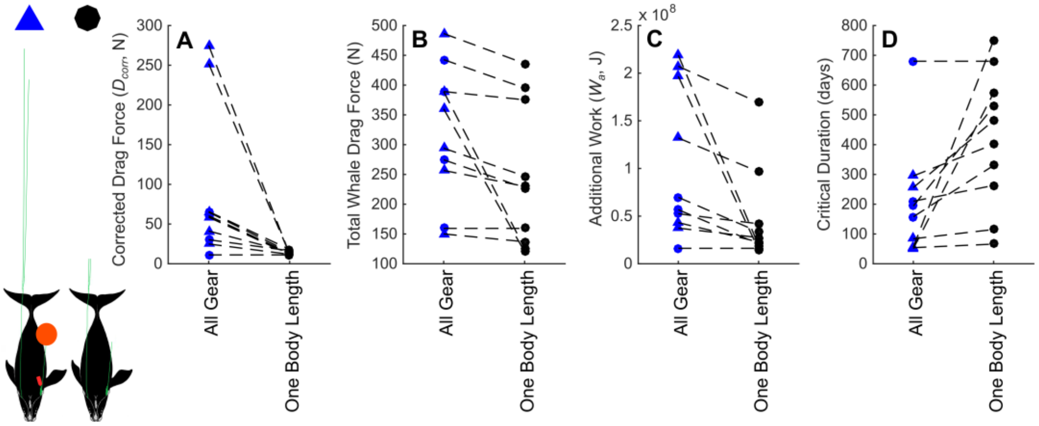


Figure 4. Partial disentanglement reduces drag and work, and increases critical entanglement duration. Corrected gear drag force (A), total whale drag force (B), additional work required to swim for 1 day (C) and critical entanglement duration (D) for ten North Atlantic right whales based on the fishing gear they were entangled in (blue), and that same gear when shortened to one body length, and with any floats or traps removed (black). See schematic to left. Circles represent gear sets with only line; triangles represent gear sets with additional floats or buoys.

Sensitivity to Gear Parameters

The critical duration estimate can include a range of gear specifics describing length, diameter, or attachment points and either the presence/absence or the dimensions of floats depending on the information available. The ten cases assessed in this study include the most refined estimates (all of the information). The sensitivity of the estimates of critical duration using different levels of information for each of the ten cases results in an average of 87(± 41) days difference (range 42-156; Figure 5). Including specific gear and float dimensions refines estimates but does not necessarily lead to more conservative or more liberal estimates. For example, including all gear and float dimensions can lead to a more conservative estimate if the float dimensions are smaller than the average floats that were measured in van der Hoop et al. (2016), resulting in a longer critical duration. Including dimensions can also lead to a less conservative estimate if gear is attached in a particularly disruptive configuration or if floats are larger than the average of the floats that were previously measured, resulting in a shorter critical estimate than would be estimated by simply gear length and float presence alone (Figure 5).

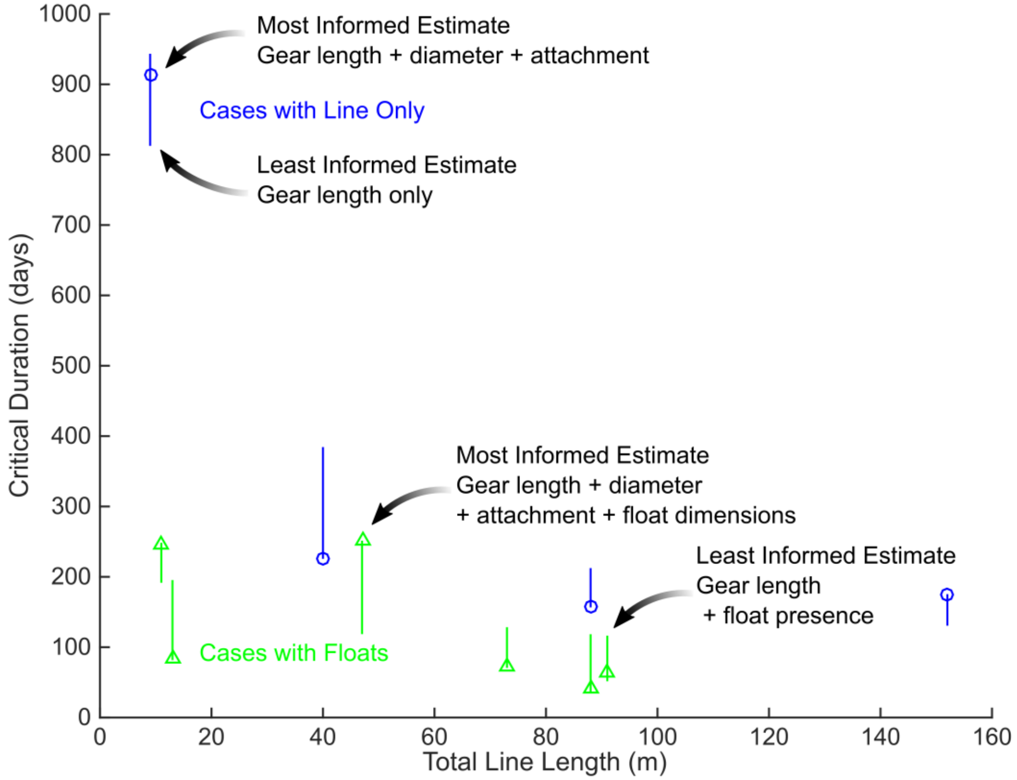


Figure 5. Uncertainty in gear configuration affects critical duration estimate by ~3 months. Estimates of critical duration (days) for 10 right whale entanglement cases made with different levels of gear information to show the effect of uncertainty in the gear configuration. Lines represent the range of critical duration when estimated with different levels of information; symbols denote the most informed estimate. Green is used for cases with floats, whereas blue represents cases with line only.

Discussion

Whales often become entangled in fishing gear, and can swim freely with a portion of gear attached to them. A combination of factors affect entanglement outcome, including gear strength and injury severity (Knowlton et al., 2016), individual condition (Pettis et al., 2004), and health impacts, entanglement duration and response efforts (Robbins et al., 2015). Post-entanglement survival has been linked to the additional energy consumption to overcome extra drag forces incurred over the duration of the entanglement (van der

Hoop et al. Accepted Ecol and Evol). This study compares measured and theoretical drag forces for configurations of fishing gear that have entangled or are similar to those entangling right whales, in order to estimate the drag on entangled whales at the time of their detection and to determine the potential time frame of their survival.

The consistent offset of measured to theoretical drag forces (e.g., Figures 1, 2) suggests that correcting values estimated from theory by a certain factor (Eqs. 10-12) can contextualize estimates of drag on unmeasured gear sets and enable comparisons with previously collected data. The consistent difference could be due to measurement (e.g., instrument sensitivity) or wave effects (e.g., propeller wash or hydrodynamic shielding from the vessel towing the gear) during the experiment that would have affected all measured gear sets in the same way. Correcting theoretical values to a standard, being the drag force measurements presented in van der Hoop et al. (2016), is essential to understand the relative risk of certain gear configurations in the context of previous studies as well as the impacts of drag loading on free-swimming animals.

Assessing Documented Entanglements

Ten right whale entanglement cases were documented with the necessary gear and individual information to estimate drag from theory and correct these values for comparison to previously measured drag forces (Appendix II). These ten cases are expected to be lethal after 216±260 days (~7 months; range 38-914 days, ~1.25 months to 2.5 years). This agrees with the observation in Moore et al. (2006) that most entangled right whales die within 6 months (182 days) to 1 year; however, entanglements can last much longer (Figure 6). The minimum entanglement durations exceeded the critical duration only once (Eg 3120, Figure 3D).

Eg 3120 survived after being entangled for a minimum of 433 days, though the drag imposed by the known dimensions of the gear configuration was expected to be lethal within 250 days (Figure 3D). The entanglement was complex, crossing over the rostrum, with wraps and buoys at the peduncle; the drag from the gear contributed 38.9% to the total drag on the animal (Figure 3A). When observed 45-150 days into its entanglement, Eg 3120 appeared to be in good health, was in proximity of other whales and was feeding and defecating. 90 days later, the nuchal fat roll appeared diminished, suggesting poor body condition (Pettis et al., 2004). A partial disentanglement was successful in removing tail wraps on 24 August 2002, 243 days after its last gear-free sighting 23 Dec 2001 and 138 days after first entanglement detection 7 April 2002. The critical duration was not re-evaluated following partial disentanglement, as no data were available on the remaining gear but the partial disentanglement was conducted before the critical duration was reached. In a sighting 180 days after the partial disentanglement, the whale’s overall condition appeared to have improved. Subsequent observations confirmed Eg 3120’s increasing health status, and that the rest of the gear had been shed on its own. Depending on the health at the time of entanglement, a partial disentanglement occurring within the critical duration timeframe, and the ability for individuals to continue to feed (based on the time of year, location, the entanglement configuration and the effectiveness of disentanglement efforts; van der Hoop et al. Accepted Ecol and Evol), individuals are able to persist with and recover from complex entanglements that initially impose substantial energetic costs.

Two whales died before their critical entanglement duration was reached. Eg 2151 died after observed minimum and maximum entanglement durations of 1-99 days, much shorter than what was expected to be lethal given the amount of attached gear (i.e., the critical duration; 914 days; Figure 3D). The whale was last seen gear-free in August 1994, in good health near the end of the feeding season. At its first entangled sighting in November 1994, Eg 2151 had a tightly constricting wrap around its rostrum and upper jaw line, potentially embedded in the oral rete or impairing feeding. The whale appeared in poor condition with a heavy load of orange cyamids and thin appearance. Poor health, severe injuries, stress and the potential for feeding impairment, on top of increased energetic demand, may have led to a more rapid demise of this individual than expected, reflecting the other factors at play in survival.

In contrast, the cause of death of Eg 1238 was likely peracute underwater entrapment rather than chronic entanglement (Moore et al., 2013). Entanglement wounds did not have chronicity to them, with no signs of healing and no major cyamid proliferation. Had Eg 1238 not drowned, this method predicts a critical entanglement duration of 158 days. However, this case illustrates that gear is lethal in many different ways – long-term energy depletion, short-term severe injury or here, peracute entrapment.

The critical entanglement duration was therefore not entirely predictive of individual fate, as there is more to entanglement survival than just energetics. The configuration of the entanglement if it interferes with feeding, the timing of and body condition at the onset of entanglement (e.g. Eg 2151; van der Hoop et al. Accepted Ecol and Evol) and the different types of entanglement injuries (e.g. Eg 1238; Cassoff et al., 2011; Moore et al., 2013) are important elements to consider. Additionally, drag is estimated from retrieved gear only: even in the event of full or partial disentanglement, not all gear is retrieved or measured. This study did not attempt to estimate drag from any remaining or unretrieved gear (e.g. the heavy monofilament line involved in Eg 3392; Appendix I) because of a lack of scaled photographs with sufficient detail for all cases. Drag estimates for this case are therefore an underestimate and present a conservative estimate of the critical duration. Despite these limitations, critical entanglement duration is still useful in that it conservatively captures the energetic component of entanglement which can be combined with other elements to assessing entanglement cases in real time or retroactively under protected species evaluations (see below).

The ten cases presented here also represent a biased sample in that the whales for which gear is retrieved and analyzed are often disentangled or whose carcasses were discovered; eight of these ten cases were fully or partially disentangled very soon after their initial entanglement detection (minimum entanglement durations were mostly 1 day; Table 2) compared to other right whale cases (Figure 6A vs. B, C). Two cases had gear retrieved from carcasses (Table 2). Many chronically entangled whales are unable to be disentangled, and the likelihood of carcass detection or discovery is greatly reduced in these cases due to decreased body condition and therefore buoyancy; whales with limited blubber reserves likely sink at death. Specific data on the types and dimensions of gear involved in these chronic entanglement cases are therefore more difficult to obtain but for many cases, even those with incomplete gear information, this approach could provide a mechanism for obtaining a crude critical duration estimate to assist real-time decision making and stock assessment.

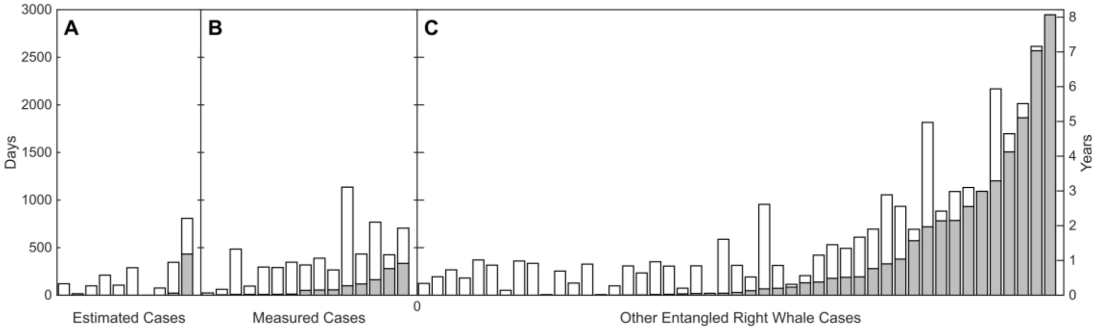


Figure 6. Minimum (grey) and maximum (white) entanglement durations (days) for right whale cases where drag forces on gear were Estimated (A; *n* = 10), Measured (B; *n* = 15), and for cases where insufficient data were available to estimate drag forces (C; *n* = 47).

Application to Entanglement Assessment: Real-Time

When a whale is reported as entangled, a trained disentanglement team will develop a response action plan using information provided in the initial report. This plan confirms the entanglement and determines whether or not the whale is a candidate for disentanglement response based on the status of the population or stock, the gear characteristics, and the configuration risk of the entanglement on the individual (IWC, 2010). The entanglement configuration, based on verbal description or as it is captured in photographs, is assessed to determine the likelihood that the whale will shed the gear on its own, whether the whale is free-swimming or anchored, and the type and amount of gear involved. While considering human and animal safety as well as available resources, disentanglement operations are prioritized based on the health of the individual and the configuration of the entanglement. This study provides a method for real-time estimates of the drag imposed by the entanglement, and how long a whale entangled in a given gear configuration may survive, which can contribute to current assessment and response procedures.

Of the ten cases in this study, eight were fully or partially disentangled within 1 to 51 days of entanglement detection (Figure 3D). Robbins et al. (2015) show that most entanglement deaths occur within the first year of detection, and that human intervention increases survival probability, especially in the most high-configuration-risk cases. Even partial disentanglement can substantially reduce drag and therefore energetic impacts. Floats and buoys add 39 N of drag, so removing these additional elements can greatly reduce the total drag of entangling gear. van der Hoop et al. (2016) showed that cutting trailing line by 75% can decrease parasitic gear drag by 85%; the current study demonstrates that reducing line to one body length and removing floats can extend the critical duration of these 10 entanglement cases by 304 days on average (Figure 4D). Follow-up response to disentangle whales requires re-sighting of an individual or tracking. While the telemetry buoy adds drag (van der Hoop et al. 2015, van der Hoop Accepted ESR), it provides significant benefit in re-sighting an individual and increasing safety for the responders (IWC 2010; IWC 2011). The results of this study allow for the impact of the addition of the telemetry buoy to be directly assessed in the context of the condition of the whale, and considered with the direct benefit in increasing the success of future disentanglement attempts. Early intervention is important to limit the deterioration of body condition and the compounding effects of low energy availability, injury and stress on individual health that could otherwise reach non-recoverable states.

Application to Entanglement Assessment: Federal Injury Assessment

The National Marine Fisheries Service (NMFS) is required to estimate annual levels of serious injury to marine mammals under the U.S. Marine Mammal Protection Act. Serious Injuries (SI) are those that may not be immediately lethal, but that are “more likely than not to result in mortality” (NMFS, 2012). The categories and criteria for large whales currently consider constricting wraps and deep lacerations as SI (Cole and Henry, 2013). While both of these situations are likely associated with the drag forces imposed by entangling gear and their duration, the evaluation criteria can and should apply the methods presented herein to incorporate energetic expenditure. Based on a limited sample set, van der Hoop *et al*. (Accepted Ecol and Evol) determined that the amount of drag (and the resulting power required to overcome it) from entangling gear was not itself a predictor of the fate of entangled individuals; however, the amount of time over which the additional energetic costs are incurred (i.e., work) is what affects individual health and survival; entanglement cases with higher drag will have shorter critical entanglement durations. Based on the results presented here, it is suggested that cases where the known or presumed duration of the entanglement exceeds the estimated critical duration should be considered SI. Appendix II includes a graphical approach and simplified formulae to be provided to those in charge of making SI determinations for NMFS.

As an example, these results and new formulae can be applied to three right whale cases: one that is not SI (Eg 4057), one where SI should be increased depending on future sightings (Eg 3111), and one where the whale is presumed dead and where critical duration gives additional certainty that the SI value should be increased to 1 (Eg 1019; Figure 7). Eg 4057 was observed entangled off Florida in February 2014 with extensive wounds at different stages of healing, though the entanglement appeared simple. With line woven through the baleen and trailing with no body wraps, the entanglement was defined as non-SI. Born in 2010, Eg 4057 was three years old at the time of entanglement detection. From age-length-drag curves (Figure A1), it is estimated that body drag for Eg 4057 swimming at 1.2 m/s is 147 N. The gear on Eg 4057 was described as 155 m of line, including a portion trailing 30 m aft of the flukes. No floats or buoys were involved in the original entangling gear. From van der Hoop et al. (2015), the entangling gear added 81.5 N of drag across speeds of 0.5-3.0 m/s. Assuming 1.6 cm (5/8") diameter line, the corrected drag (D_{corr}, Eq. 10) from the theoretical estimate (D_{theor}, Eq. 1) is 89 N. The interference drag (D_I) in this case is negligible, <1 N. Together, these estimates suggest a minimum critical entanglement duration of 118 days, which would be 14 June 2014 (Figure 7A).

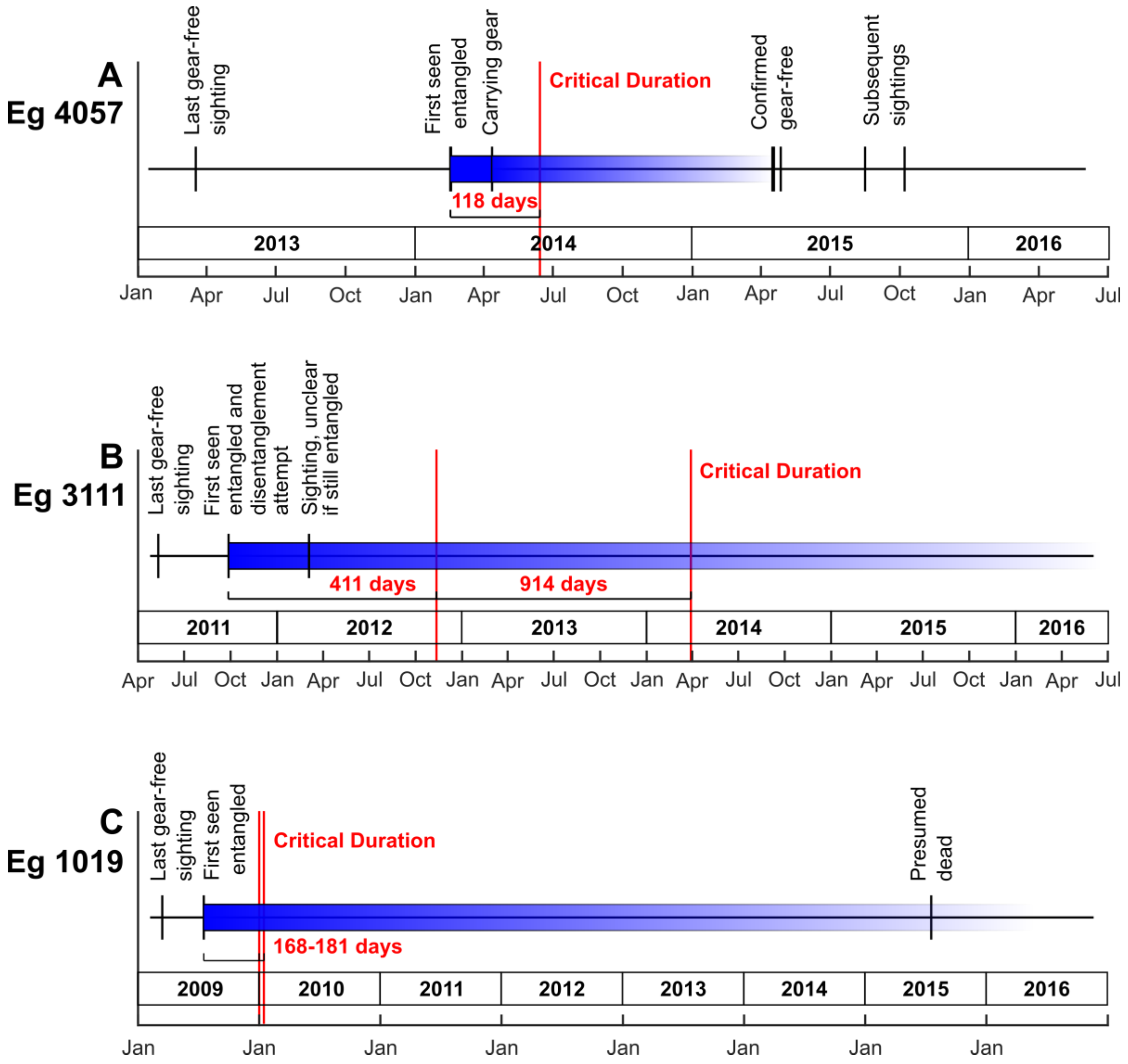


Figure 7. Instances of sighting (vertical black lines) during the entanglement timelines of right whales Eg 4057 (A), Eg 3111 (B) and Eg 1019 (C). Onset and duration are shown in blue, with the proposed critical entanglement duration for classification as Serious Injury (SI; red). The entanglement in panel A fades as the entanglement was shed between those confirmed sightings. Panels B and C fade through time as the animal may have shed gear during that time and the likelihood of present entanglement decreases with time, but note the method assumes no change in the gear during the entangled duration since last observation. Date ranges are due to uncertainty in gear dimensions on whales B and C.

Eg 4057 was sighted still carrying gear on 12 April 2014, 55 days from the initial entanglement detection. A year later, multiple sightings in April 2015 confirmed that Eg

4057 was gear-free. Based on this timeline, Eg 4057's entanglement does not fit the proposed SI criterion in that it was not observed carrying gear beyond the minimum critical entanglement duration, i.e., the whale apparently shed the gear before the 147 d threshold. Entanglements that have lasted longer than the minimum critical duration should be considered serious injury, i.e., had Eg 4057 been sighted still carrying gear after 13 July 2014 or if retroactive analysis of catalogued photographs reveal evidence of entanglement at an earlier date (Figure 7A). It is common for whales to be already in compromised condition when first detected with gear. In this event it can be assumed that the whale had already been entangled for some period of weeks to months, but such a presumed duration cannot be added to the observed entanglement duration due to too many unknowns; future research to determine the rate of observable health declines or changes in body condition could enable these types of estimates.

Eg 4057 is a data-rich case, in contrast to Egs 3111 and 1019. Poorly documented cases often fall under more generalized SI criteria (e.g., L10) where they are prorated by 0.75 to account for uncertainty (Cole and Henry, 2013; NMFS, 2012). Eg 3111 was first sighted entangled in Sept 2011, and a disentanglement attempt occurred that same day. This attempt may have removed a portion of the gear, leaving 6-36 m remaining for a critical duration of 411-914 days. The whale was resighted 159 days later in March 2012 (Figure 7B) with improved skin condition and no gear was visible. However, sighting conditions prevented confirming if Eg 3111 had shed the remaining gear and the whale has yet to be seen since. If Eg 3111 is entangled at its next sighting or if it is not seen again by March 2018 and is therefore presumed dead, SI should be increased from 0.75

to 1. Eg 1019 was first seen entangled July 2009 with no further sightings, and was presumed dead in July 2015. A critical duration of 168-181 days was estimated based on 21.3-30.5 m of line with a 20” ball buoy. The SI value for this case is 0.75 but should be increased to 1: the critical duration gives additional certainty that the whale is more likely than not dead, i.e., seriously injured by definition (NMFS, 2012).

For this application, critical duration estimates should be adjusted following partial disentanglement (e.g., removal of floats, reducing training line) as small reductions in drag can significantly increase an individual’s endurance (Figure 4D). However, if the disentanglement occurs after the critical duration is reached, the case should still be considered SI: energetic impacts may have already been sufficient to affect health and reduce survival probabilities even after disentanglement (e.g., Eg 3911; Moore et al., 2012; van der Hoop et al., 2013b).

Methodological considerations

Separating the lobster trap, telemetry buoy, and gillnet from the other gear sets is warranted based on the difference in the relationships between measured and theoretical drag, but also based on the gear characteristics themselves (Figure 2). The lobster trap and telemetry buoy are not only large and poorly streamlined, but are also heavy – the two-brick trap weighing 15.7 kg (34.6 lbs) and the telemetry buoy 18.2 kg (40.1 lbs) are the two heaviest sets of gear measured. In cases where there is evidence of weight attached to the trailing line, the equation for the lobster trap should be used. Although the amount of weight may not be known at the time of entanglement detection, the two-brick trap tested here (34.6 lbs) is lighter than most used in the Gulf of Maine lobster fishery (40-65 lbs; McCarron and Tetreault, 2012). Other pot gear may be lighter (e.g. blue crab ~20 lbs) or heavier (e.g. snow crab ~40 lbs), or when whales tow more than one trap. Gillnet gear has a much lower measured drag than is expected from theory, likely due to the high surface area of the large mass of tangled gear (Figure 2). Water flow through or around the tangled mass is unknown, especially when it is wrapped around the whale's body. Drag is easier to estimate for simpler sets of gear (e.g., trailing line, Figure 1) or those with well-described accessories (e.g., floats or buoys, Figure 2); it is more difficult to estimate drag on gear that wraps the body. Computational fluid dynamics (CFD) may prove a more useful way to investigate the flow properties, drag conditions, and energetic cost associated with these types of entanglements.

There are now three ways to estimate drag from entangling fishing gear at the time of first entanglement: the methods presented herein, and the weight-drag and length-drag equations presented in van der Hoop et al. (2016). Whereas dry weight can be assessed long after gear is recovered from an animal that has been disentangled, this method is least likely to be beneficial when whales are first reported entangled. Gear length, however, is frequently described in entanglement reports. The length-drag equation in van der Hoop et al. (2016) requires only the length of the gear and the presence of floats to estimate the average added drag across all measured speeds (1.27 m/s) with comparable fit (R^2 = 0.812, RMSE = 21.2 vs. R^2 = 0.846, RMSE = 27.2). Estimating drag from theory incorporates not only the length of the line and the presence of floats, but also their dimensions (e.g., diameter, shape) and interference drag from the point of attachment. While interference drag can be insignificant in many cases (Figure 3A; example of Eg 4057 above), it can contribute up to 75% of total gear drag in others (e.g., Eg 1971, Figure 3A) where line wraps the body multiple times or where floats are located at the body's surface rather than trailing behind. Drag also can be estimated at whatever swimming speed is observed, depending on the behavior or health status of the animal; in this study, it is assumed that individuals maintain swimming speeds of 1.23 m/s, but speed is not always maintained in high drag conditions (van der Hoop et al. Accepted ESR; van der Hoop et al., 2014) and right whale swimming speeds can range 0.4-4 m/s (Hain et al., 2013; Mate et al., 1997). Overall, drag should be estimated from theory and corrected to measured drag even with insufficient detail or a range of gear dimensions with an acknowledgement of potential inaccuracy and using the more conservative estimate e.g., Egs 3111 and 1019 above, where 30 m and 10 m differences in gear length estimates led to 503- and 13-day differences in critical durations (Figure 7B, C). Sensitivity analyses show that using different levels of information to describe the same gear configurations yields on average 87 day differences in critical duration estimates (Figure 5). The most informed estimate is not necessarily the most or least conservative, though it is the most accurate and most refined. The range in estimated critical duration is often within sightings gaps of entangled whales (e.g., Figure 7); it is therefore still useful to estimate this range with limited information for inclusion Serious Injury determinations at the federal level.

The relationships established herein were applied to well-documented entanglement cases, where gear was removed, recovered, and measured. Efforts to recover gear from disentanglement operations or at death have allowed for a better understanding of the types of gear that frequently entangle whales, their common configurations on certain species (Johnson et al., 2005), their breaking strengths (Knowlton et al., 2016) and the drag forces they add to entangled animals (van der Hoop et al., 2016; van der Hoop et al., 2013b). Even with disentanglement response, gear cannot be always be recovered; the majority of entanglements are only observed and described at sea. Estimates of range and size by humans are often inaccurate (~10%; Rohner et al., 2011) and variable (Øien and Schweder, 1992), though the magnitude, bias, and variability of estimation error decrease with experience (Baird and Burkhart, 2000). The methods presented in this study should be applied to cases where gear configurations are well documented (e.g., with photographs or video with a scale or reference object) or are described by experienced observers. This would ensure that gear dimensions, from which drag and survival estimates are derived, are as accurate as possible.

Acknowledging Variability

The assessment of the critical duration is based on the additional energy required to overcome increased thrust production associated with entanglement drag (see Eq. 9). As such, the estimate is robust to uncertainty in whale age or length. It does not, however, take into account differences in energy stores available for different age or sex classes of whales.

This and previous studies (Johnson et al., 2005; van der Hoop et al., 2016; van der Hoop et al., 2013b) show the variability in the types, dimensions, components, and configurations of gear that entangle right whales and other large whales. Variability in these elements affects the total drag; further, the points of attachment and the dimensions of the gear at the attachment points affect the relative contribution of interference drag vs. total drag (Figure 3A). Photographic and video documentation of the gear with spatial references or measurements are extremely helpful in estimating gear dimensions and placement on the whale. Efforts to document and draw entangling configurations have proven extremely useful for disentanglement response (IWC, 2010), for determination and definition of serious injuries to protected species (Moore et al., 2013; NOAA, 2008), and for assessment of the hydrodynamic effects of entanglement (herein; van der Hoop et al., 2016; van der Hoop et al., 2013b).

There is also considerable variability in the dimensions of the whales that become entangled. Right whale calves and juveniles are more frequently found entangled than other life stages; though they make up only 29% of the population, over 50% of seriously entangled right whales are juveniles (Knowlton et al., 2012). Similar trends hold in humpback whales (Knowlton et al. 2016) and other species (Fowler, 1987; McIntosh et al., 2016; Moore et al., 2009). The high incidence of entanglement in smaller animals means a larger relative size of the gear to the animal: gear with the same dimensions would contribute a greater amount to the animal’s total entangled drag (Figure 3A). Swimming costs are therefore proportionally greater for smaller animals (Feldkamp, 1985).

Over the lifespan of a right whale (up to 70 years; Fortune et al., 2012), body length increases by ~10 m, and girths by ~1.6 m (Fortune et al., 2012). Other natural life events can alter body shape significantly: pregnant right whales increase 4-25 cm in width in various positions along the body, lactating southern right whales (*Eubalaena australis*) can lose 21.8 ± 6.1 cm in 3-4 months (Miller et al., 2012) and migration can lead to significant reductions in body width (Perryman and Lynn, 2002) and weight (11-29%; Rice and Wolman, 1971) in gray whales (*Eschrichtius robustus*). Unnatural, though extremely common in the right whale population (Knowlton et al., 2012), chronic entanglement in fishing gear can reduce body diameter by 20% compared to mesomorphic right whales (van der Hoop et al., 2013b) and can reduce body weight by 28% (Barratclough et al., 2014). Almost all (49/50) photo identified entangled right whales are in good body condition at their last sighting prior to entanglement detection (Robbins et al., 2015).

Changes in body shape will affect whales' hydrodynamic efficiency and the relative contribution of gear drag, at variable and unknown rates (Appendix III). If an adult whale (e.g., Eg 1223; 12 years old, 13.6 m, 32670 kg measured at necropsy; Barratclough et al., 2014) loses 28% of its body weight and 20% body diameter over the course of its entanglement, the whale's drag coefficient would decrease by 6.5% (0.0062 to 0.0058) and its fineness ratio (body length/width) would increase by 25% (4.64 to 5.81), away from the optimal 4.5 (Ahlborn et al., 2009; Hoerner, 1965). These changes in body weight and girth would decrease drag by 24%. In contrast, while maintaining body condition, the increase in length from juvenile (e.g., 2 years old, 11.1 m) to adult (e.g., 28 years, 14.7 m; a 33% increase) life stages leads to a 72.3% increase in drag force, and a 6% increase in drag coefficient, while the fineness ratio is essentially unchanged. There is therefore an interplay between increases in length with age, and decreases in body condition with entanglement duration, along with the nonlinear dynamics of both, that will be unique for every entangled whale based on age, configuration, health status, geographic location, and time of year. The estimates herein begin to combine these elements in their simplest form – considering individual length and girth at the onset of entanglement – but do not consider the intricate dynamics of these body shape changes and their effect on the drag regime.

Conclusions

It is possible to estimate drag from fishing gear at the time that an entangled whale is detected or reported. These estimates can be incorporated into the case assessment and development of disentanglement action plans (IWC, 2010). The observed and estimated critical entanglement durations should also be included in the decision-making process and can be valuable in determining whether entanglement cases are life-threatening or qualify as ‘Serious Injuries’ for federally protected species (NOAA, 2008). This method could also be applied to other large whale species with significant entanglement-related mortality and injury rates (Cole and Henry, 2013; van der Hoop et al., 2013a).

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Appendix I. Wetted areas of floats or traps on unmeasured gear sets

Whale Eg 1427, Gear J071212: 46 cm diameter buoy

Buoy A_w $\frac{m}{}$ m

Whale Eg 1971, Gear J062497: 43 cm diameter buoy (A3 Polyform)

Buoy A_w $\frac{m}{}$ m

Whale Eg 2427, Gear J072001: 43 cm diameter buoy (A3 Polyform)

Buoy A_w $\frac{m}{}$ m

Whale Eg 2753, Gear J060599: LD-3, 34.3 cm × 73.7 cm Scan float

Buoy A_w, based on an ellipse with a = 0.3685 and b = c = 0.1715, using Knud Thomsen's formula, where p = 1.6075,

$$\frac{\frac{}{}^{-}}{} \quad 0.336\,\text{m}^2$$

Whale Eg 3120, Gear J040702: 13 × 28 cm lobster buoy

Buoy A_w, assuming the buoy is a half ellipsoid with a = 0.14 m; b = c = 0.064 m as above, =

Whale Eg 3392, Gear J070903: 0.91 × 0.61 × 0.30 m lobster trap and 15 × 33 cm lobster buoy

Buoy A_w, assuming the buoy is a half ellipsoid with a = 0.17 m; b = c = 0.075 m as above,

= 0.0656 m^2

Trap A_w, assuming 0.038 m (1.5”) mesh size and 0.0025 m (1/10”) wire diameter:
The trap consists of six panels, two each of (a) 0.91 × 0.61 m, (b) 0.61 x 0.30 m, and (c) 0.91 x 0.30 m. The mesh area (A_M) of each panel (a, b, c) was calculated as:

$A_M = N \quad K \quad 2M \quad W$,

where N is number of wire columns, K is number of wire rows, M is the mesh size and W the wire diameter. The number of columns and rows is determined by the size of the panel divided by the mesh size (Fridman and Dvernik, 1973; Reid, 1977).

= 0.268 m^2

Total Aw = 0.268 m^2 + 0.0656 m^2 = 0.336 m^2

This whale also had heavy gauge (~5/16” dia) monofilament line wrapped around the peduncle, likely as a result of a separate and previous interaction. Drag on this gear was not estimated as no measurements were available. Drag estimates for this case are therefore an underestimate.

Whale Eg 3821, Gear J092609: 1.06 m × 0.61 × 0.30 m lobster trap

Trap A_w, assuming 0.038 m (1.5”) mesh size and 0.0025 m (1/10”) wire diameter:
The trap consists of six panels, two each of (a) 1.06 × 0.61 m, (b) 0.61 x 0.30 m, and (c) 1.06 x 0.30 m. The mesh area (A_M) of each panel (a, b, c) was calculated as:

$A = N \quad K \quad 2M \quad W$,

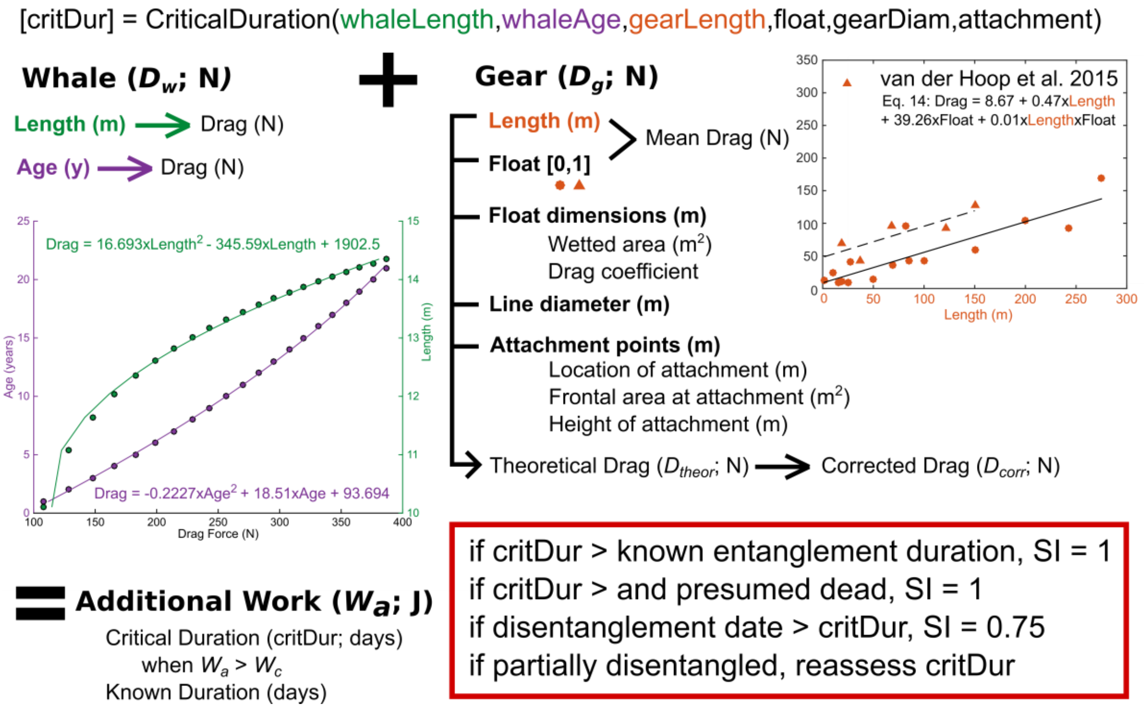
where N is number of wire columns, K is number of wire rows, M is the mesh size and W the wire diameter. The number of columns and rows is determined by the size of the panel divided by the mesh size (Fridman and Dvernik, 1973; Reid, 1977).

= 0.304 m^2

Appendix II. Guide for calculating minimum entanglement duration for Serious Injury (SI) determinations

Motivation: The known or presumed duration of an entanglement should be considered as a criterion in Serious Injury (SI) determinations. We suggest that this duration be compared to the critical entanglement duration, the time it takes for additional energy expenditure (W_a, J) to reach the threshold lethal energy expenditure level (8.57×10^9 J) in van der Hoop et al. (Accepted Ecol and Evol). A MATLAB function (CriticalDuration.m) calls upon multiple functions and scripts developed for and from the equations in this paper and provides a simplified method to assist SI determinations.

Procedure: A graphical representation of the MATLAB function CriticalDuration.m is provided below. The minimum inputs to the function are the whale's length (whaleLength; m) or age (whaleAge; years) and the length of the entangling gear (gearLength; m) and presence or absence of floats (float; binary 0 or 1). Additional information on the dimensions of the floats, the diameter of the line, and the attachment points of gear on the whale will help refine the estimate of theoretical drag (D_{theor}; N) which is then corrected to units comparable to those measured for this and previous studies (van der Hoop et al., 2016). The whale and gear drag are combined to estimate the additional work (W_a; J) required for the entanglement, from which the critical duration is determined. We suggest that a criterion for SI be if the critical duration exceeds the known entanglement duration.



Appendix III. Changes in whale drag with body dimensions

Motivation:

Morphology and morphometry differ among marine mammal families, likely related to specialization for foraging modes and ecological niche. Even closely related species (e.g., balaenopterids) show surprising morphometric differences that can affect their swimming performance and hydrodynamics (Woodward et al., 2006).

Within a species, considerable morphometric variation exists. Over the lifespan of a right whale (up to 70 years; Fortune et al., 2012), body length increases by ~10 m, and girths by ~1.6 m (Fortune et al., 2012). Other natural life events can alter body shape significantly: pregnant right whales increase 4-25 cm in width in various positions along the body, lactating southern right whales (*Eubalaena australis*) can lose 21.8 ± 6.1 cm in 3-4 months (Miller et al., 2012) and migration can lead to significant reductions in body width (Perryman and Lynn, 2002) and weight (11-29%; Rice and Wolman, 1971) in gray whales (*Eschrichtius robustus*). Unnatural, though extremely common in the right whale population (Knowlton et al., 2012), chronic entanglement in fishing gear can reduce body diameter by 20% compared to mesomorphic right whales (van der Hoop et al., 2013b) and can reduce body weight by 28% (Barratclough et al., 2014).

How do these changes affect hydrodynamics and drag forces on a whale's body?

Methods:

The theoretical rigid-body drag force (F_D; N) was calculated based on a turbulent spindle model (Webb, 1975),

– ,

where ρ is seawater density (1025 kg/m^3), U is swimming speed (m/s), and A_w is the total wetted surface area (m^2) calculated from body weight W (kg) as $A_w = 0.08W^{0.65}$ (Fish, 1993). C_d is the drag coefficient, calculated as

– – ,

where C_f is the frictional drag component computed from the Reynolds number (Re),

– ,

and d and l are the maximum body diameter (m) and total body length (m) of a right whale.

To determine how total body drag, drag coefficient, and fineness ratio (FR; l/d) change with body dimensions, d, l, and W were varied to reflect the morphometrics of (1) four right whales of varying ages, lengths, and body conditions (Table A1), (2) a mesomorphic right whale from age 2 to 28 with body length- and width-at-age from Moore et al. 2004 and Fortune et al. 2012, and (3) right whale Eg 1223 (Table A1) with constant body length but with reductions of 28% in body weight (Barratclough et al., 2014) and 20% in maximum body diameter (van der Hoop et al., 2013b; Figure 2C).

Table A1. Individual ID, age, measured length (m), weight (Kg), diameter (m), and notes on the body condition or cause of death of four North Atlantic right whales.

Whale ID	**Age**	**Length (m)**	**Diameter (m)**	**Weight (Kg)**	**Notes**
Eg 3911	2	10.0	2.20	7000 (E)	Entangled, emaciated
MH89-424-Eg	<1	4.12	0.719	1227 (W)	Perinatal
Eg 1014	28	13.70	2.96	52640 (S)	Vessel Collision
Eg 1223	12	13.60	2.93	32670 (W)	Vessel Collison

The percent change in drag coefficient, total body drag force, and fineness ratio were calculated between the minimum and maximum values (1) of the four whales or (2, 3) of the range obtained from varying different body dimensions.

Results

Drag increases with body size (Figure A1A), where at 1.2 m/s (95% CI swimming speed; (Baumgartner and Mate, 2005)) drag ranges from 34 – 327 N, a 162% difference. Drag coefficients range 2.9E-3 to 3.6E-3, differing no more than 20%, while fineness ratios vary by 24%, from 4.55 to 5.73.

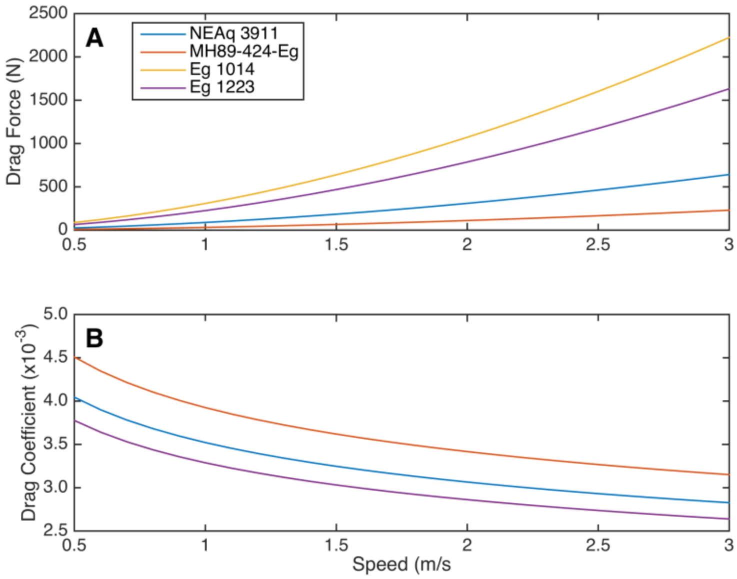


Figure A1. Drag forces (A) and coefficients (B) of four North Atlantic right whales of different body dimensions across modeled speeds.

During an individual's growth from age 2 to 28, the total drag forces increase by 72%, from 123 to 437 N at 1.2 m/s (Figure A2A). The drag coefficient decreases 7.1% (Figure A2B). With normal growth, the fineness ratio remains almost unchanged at 4.19 (range 4.08-4.23; a 3.7% change; Figure A2C).

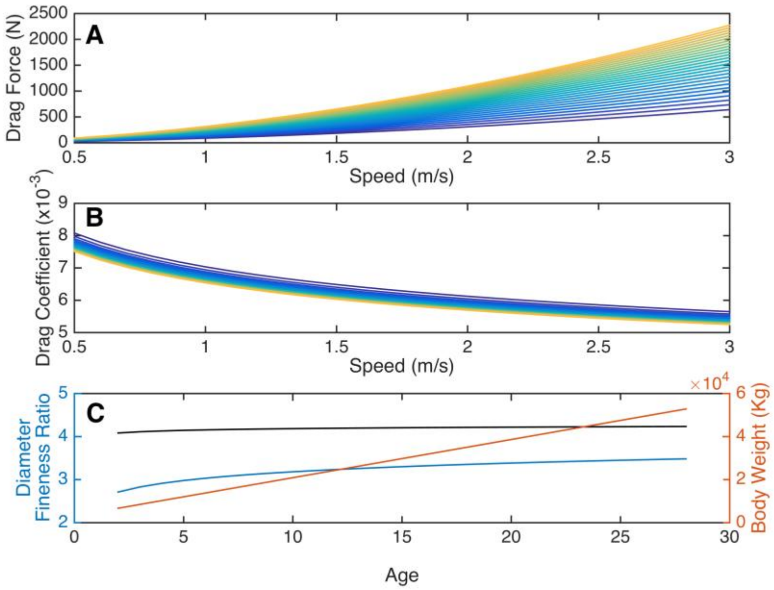


Figure A2. Total body drag force (N; A) and drag coefficient (B) with speed modeled for a North Atlantic right whale from age 2 (darkest blue) to 28 (yellow), and modeled body diameter (blue), fineness ratio (black) and body weight (orange) with age.

As body width and weight decrease through the course of an entanglement, an individual's total body drag force may decrease by 21.5% at 1.2 m/s, with a 6.5% reduction in drag coefficient and a 21.7% increase in FR.

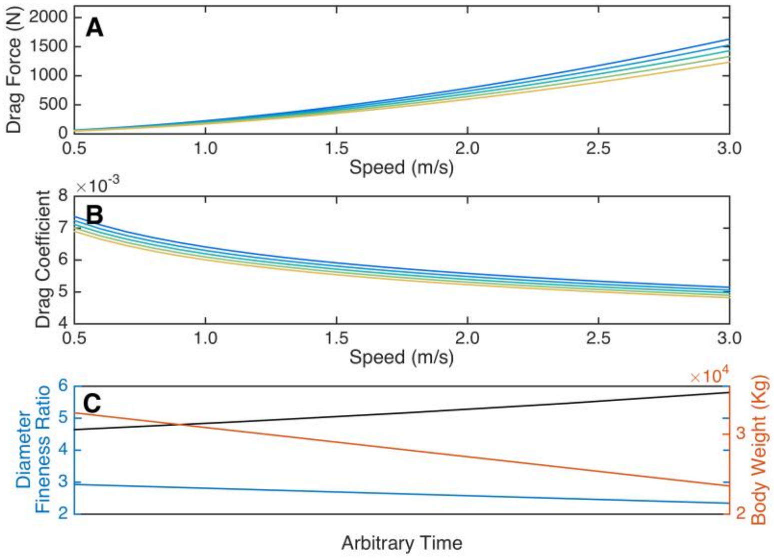


Figure A3. Total body drag force (N; A) and drag coefficient (B) with speed modeled for a North Atlantic right whale Eg 1223 with healthy body dimensions (blue) and as it loses 20% of body width and 28% of body weight (yellow). Body diameter (C; blue) and weight (orange) are reduced through time and affect the fineness ratio (black).