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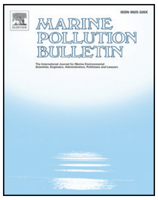

Predicting lethal entanglements as a consequence of drag from fishing gear

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ABSTRACT

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.

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1. 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 entanglement 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., 2016a; 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. 2016b); 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., 2016a; van der Hoop et al., 2013b), drag forces can also be estimated from well-established physical theory (Faltinsen, 1993; Fridman,

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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.

2. Methods

2.1. 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 (D_{meas}; van der Hoop et al., 2016a). 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

$$D_l = C_d l d q \tag{1}$$

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):

$$q = \frac{\rho U^2}{2} \tag{2}$$

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,

$$\alpha = \sin\left(\frac{z}{l}\right). \tag{3}$$

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

Drag from floats, traps or buoys is estimated as

$$D_f = C_d q A_w \tag{4}$$

where A_w is the wetted surface area (m^2) of each rigging component (see Appendix 2 in van der Hoop et al., 2016a) 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:

$$D_{theor} = D_l + D_f. \tag{5}$$

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.

2.2. Non-measured gear sets

Ten sets of fishing gear entangling right whales were sufficiently described with dimensions to estimate drag forces from theory following Eqs.(1)–(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. (2016a; 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 1). 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. (2016a).

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., 2016a). 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., 2016a; van der Hoop et al., 2013b). The total drag on each entangled whale (D_{tot}) was then:

$$D_{tot} = D_w + D_I + D_{corr}. \tag{6}$$

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

$$P_{T,e} = \frac{D_{tot} U}{\eta_e} \tag{7}$$

$$P_{T,n} = \frac{D_w U}{\eta_n} \tag{8}$$

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. (2016c). 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 ($U_e = U_n$), i.e., that animals do not slow down once entangled.

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