# *Entanglement's Effects on Baleen Filtration Fluid Dynamics in Critically Endangered North Atlantic Right Whales: Preliminary Findings*

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## Introduction

Entanglement in fishing gear and lines is a leading cause of whale mortality (Johnson et al. 2005; Cassoff et al. 2011; Moore and van der Hoop 2012; van der Hoop et al. 2013, 2016, 2017a, 2017b; Moore et al. 2021; Knowlton et al. 2012, 2022; Reed et al. 2024; Crum et al. 2025). This is especially true for the North Atlantic right whale (NARW), *Eubalaena glacialis*, which is considered the most highly endangered whale species, with a total population currently estimated at 370 individuals (NOAA 2024). Considered the "urban whale" for its coastal habitat in close proximity to major cities (Kraus and Rolland 2010), this species frequently encounters ropes or cables attached to crab or lobster pots and floating buoys stretching from the ocean floor to the surface (Kraus et al. 2005; Johnson et al. 2007; Howle et al. 2019). Studies estimate that 89% of living right whales have been entangled at least once, with some whales having experienced up to eight entanglements during their lifetime (Reed et al. 2024; Whale and Dolphin Conservation 2024).

Like all mysticetes (baleen whales), right whales filter prey items suspended in seawater (Werth 2000; Goldbogen et al. 2017) with an oral filter made of alpha keratin (Werth 2001, 2017). The NARW diet consists primarily of small, rice grain-sized (1-15 mm) copepods aggregating in dense blooms at all levels of the water column, from the surface to the bottom (Werth 2004). NARW feeding generally involves bouts of slow skimming, in which the whale's oral baleen filter functions like a plankton tow net (Werth 2000, 2001, 2004), although it is propelled by a whale's forward locomotion rather than towed (Fig. 1). Because a foraging whale's baleen filter generates massive drag forces (Werth and Sformo 2020), this propulsion involves slow fluking. Due to whales' slow foraging speed and the tiny size of targeted copepods or other planktonic prey, whales must swim with their mouths open for frequent and prolonged periods (Werth 2004). Feeding NARWs are therefore at grave risk of ingesting non-food items or substances such as plastics or oil slicks contaminating waters of their feeding grounds (Knowlton et al. 2012; Borggard et al. 2017). Because NARWs typically forage in highly trafficked areas heavily used for fishing, they are highly vulnerable to encounters with fishing lines that crisscross their habitat (Kraus and Rolland 2010). Due to its basic anatomy, a whale's open mouth is generally the body part that initially contacts line and gear (Werth 2004). Thus, although entanglement often involves flippers, flukes, or flanks, the mouth is typically the body part most likely to become entangled (Cassoff et al. 2011).

The lines used in commercial fishing gear are thick and heavy because they must support and

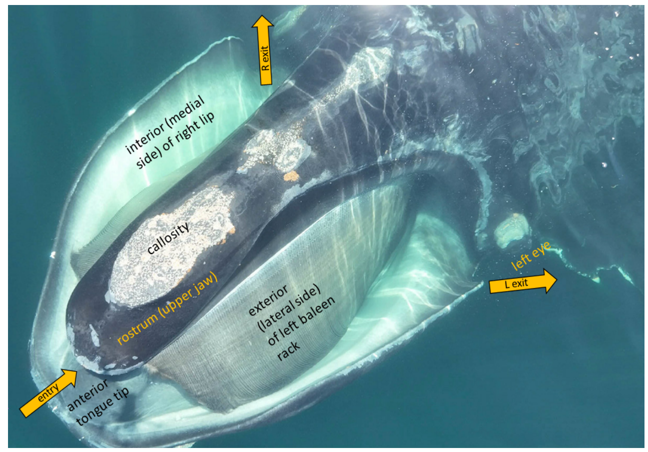


Figure 1. Dorsal (top) view of the mouth of a North Atlantic right whale (EGNo: 4425) swimming toward bottom left, showing the roughly 300 baleen plates of the left baleen rack, with the right rack partially visible on the other side of the rostrum. Like other balaenids, right whales feed via continuous filtration, with a steady stream of prey-laden water entering a subrostral gap between the paired, suspended baleen racks, and with filtered water exiting posterolaterally through each rack and out of the mouth at the posterior of each semicircular lower lip, just below the eye. This whale, completely submerged but just below the ocean surface, was photographed by an observer operating an aerial drone under NOAA/NMFS permit #594-1759.

retrieve traps weighing hundreds or thousands of pounds (van der Hoop et al. 2017a, 2017b). This potentially increases a whale's already high drag 1.5-3.1-fold (van der Hoop et al. 2017b), which makes entanglement difficult to escape from, in turn making entanglement more deadly. Not only is swimming made more difficult, but entanglement also makes feeding, breathing, mating, migrating, birthing, and other activities more difficult as well (van der Hoop et al. 2016). Records indicate that if humans do not intervene, an entangled whale may not be freed for months or years, if it lives that long (van der Hoop et al. 2017a, 2017b). Human intervention for disentanglement is notoriously challenging and dangerous for both whales as well as humans, especially when whales are stressed, confused, weakened, or surprised, and therefore misinterpret human aid, putting humans in greater danger (Moore et al. 2021). All entanglements increase the physical and psychological stresses felt by a whale, but severe entanglement has been found to cause levels of stress that mimic additional migration or even birthing events (van der Hoop et al. 2017b).

Further, entanglement is not only stressful but often lethal to North Atlantic right whales and other whales. A leading cause of death by entanglement is drowning (Cassoff et al. 2011). As mammals, whales must be able to breathe air through the blowholes located on top of their head; entanglement within subsurface lines and gear, as well as exhaustion from pulling extra weight, makes this much harder, as does a whale's likely stress, fear, and confusion. Because ropes or other lines are thick, heavy, durable, and not easily removed (Knowlton et al. 2016), they often cut through skin, muscle, and other tissues (Cassoff et al. 2011). Tension and friction from swimming and other motion drives ropes deep into flesh, slicing 20 cm or more (Cassoff et al. 2011), often leading to deep, disfiguring lacerations or amputations (Robbins et al. 2015). Wounds on the rostrum or elsewhere on the body remain raw and susceptible to disease pathogens and parasites; this too is a frequent cause of entangled whale morbidity and mortality (National Science Foundation et al. 2024).

A final common cause of death from entanglement is starvation. Whether found dead or alive, entangled whales often display signs of severe emaciation (Knowlton et al. 2012; Robbins et al. 2015; Moore et al. 2021). This is a simple consequence of stresses engendered by higher drag forces plus obvious inability to swim and feed normally (van der Hoop et al. 2013). Just as heavy lines and gear impede surfacing, entangled buoys hinder diving (van der Hoop et al. 2016). As a whale uses more calories than it consumes, it depletes its energy stores in blubber (van der Hoop et al. 2017a, 2017b). Because the mouth is the most commonly entangled part of a whale (Johnson et al. 2005), and because oral entanglement often involves lines wrapped around structures in multiple complex ways that are difficult to remove or easily resolve (Moore et al. 2021), feeding is also likely to be affected in numerous ways (Goldbogen et al. 2017). This is the focus of the research project described here. The incidence of oral entanglement has been noted by previous studies (Johnson et al. 2005; Cassoff et al. 2011; Moore and van der Hoop 2012; van der Hoop et al. 2013, 2016, 2017a, 2017b; Moore et al. 2021; Knowlton et al. 2012, 2022; Reed et al. 2024; Crum et al. 2025). However, the direct and indirect multifactorial consequences of entangling lines on baleen structure and function has heretofore received little attention, which this ongoing study aims to remedy.

How does baleen tissue itself (Werth 2017), and the arrangement and dimensions (e.g., spacing) of baleen plates and fringes, contribute to entanglement and impede disentanglement? Where in the mouth (e.g., anterior, posterior, or middle) do entangling lines most commonly become trapped, and what are the consequences of this location for the flow of prey-laden water during feeding? How does this affect the hydrodynamics of filtration? Are entangling lines likely to be trapped on both sides of the mouth, or to protrude from only one rack? How much of a difference in flow dynamics does the diameter and type of entangling line make? When entangling lines remain lodged between baleen plates, how does the lack of an open gap between those plates affect flow, both at that location and elsewhere in a rack? Alternatively, when an entangling line is removed, does a wider intra-plate baleen gap remain, and if so, what are its effects on flow dynamics?

These and other related questions are the subject of this ongoing project, which relies on multiple methods to explore how oral entanglement influences baleen's normal functions. Our study employs a three-pronged approach targeting key aspects of oral entanglement and filtration.

1) Analysis of photographs, video recorded sequences, and other images, along with detailed records documenting specific instances of oral entanglement in NARWs (and other mysticete species)
2) Experiments using actual baleen tissue or artificial structures to simulate flow through the filter, or entire mouth, of normal and entangled whales
3) Computational fluid dynamics (CFD) simulations run on mockups of NARW baleen racks to test specific controlled conditions

In addition to learning about the effects of (and ways to mitigate) entanglement, this study aims to better understand aspects of flow during normal mysticete filter feeding.

This research is ongoing at Hampden-Sydney along with multiple extramural collaborators, including Gina L. Lonati (University of New Brunswick and Marine Mammal Center), Jean Potvin (Saint Louis University), Michael J. Moore (Woods Hole Oceanographic Institution), Douglas P. Nowacek (Duke University Marine Laboratory), and Heather M. Pettis and Philip K. Hamilton (New England Aquarium and North Atlantic Right Whale Consortium).

## Materials and Methods

All images and tissues used in this study were obtained through applicable federal permits from NOAA/NMFS and other regulatory agencies. No animals were harmed for the purposes of this study. Images and information about specifically entangled whales were provided through the DIGITS database of the North Atlantic Right Whale Consortium (NARWC) operated via the New England Aquarium (NEAq) in Boston (National Science Foundation 2024). This enabled viewing of documented entanglements spanning the past two decades. Image review focused on the types and extent of entanglement, and specifically the location(s) of entangling lines within and through the oral baleen filter.

Investigation of photographs and videos from live whales, along with necropsy records, documents the scope of oral entanglement, showing where and how oral entanglements generally occur, and the resulting baleen damage that it causes, as well as how many whales are affected by oral entanglement, and what kinds of whales (e.g., by sex, age, size, body condition, etc.) are affected. This mainly involves the NEAq/NARWC DIGITS database (National Science Foundation 2024), as well as photos, videos, and records from other observers and institutions.

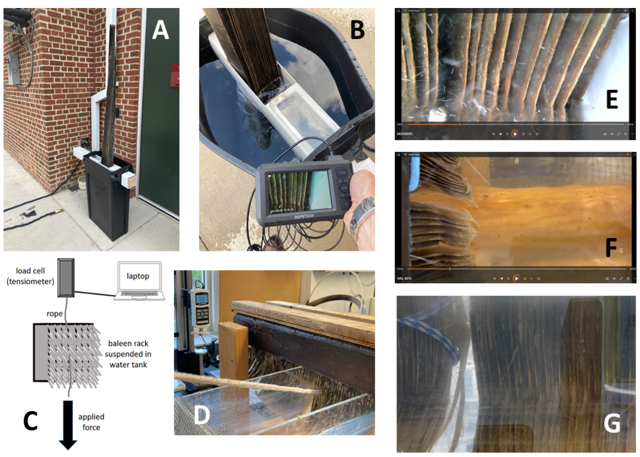


Figure 2. Tools and techniques used for experimental trials of this study: image A shows 30 plates of bowhead whale baleen projecting above a white flow tube through which water circulated near the top of a black tank of water; B shows screen of borescope recording video of flow through the baleen. C is a schematic diagram showing the setup to measure tensile forces needed to dislodge various ropes/lines lodged between baleen plates submerged in a circulating flow tank (D). E-G shows examples of freeze-frame screen grabs of video recordings analyzed to measure flow rates of buoyant particles suspended in a circulating flow tank as they flow through and near rope-generated gaps in baleen racks of humpback or right/bowhead whale baleen.

To study flow effects, a flow tank or flume was used in which cut pieces of NARW and related bowhead whale (*Balaena mysticetus*) baleen tissue were assembled into “mini racks” of 6-10 contiguous plate sections (Werth 2004, 2013; Werth and Potvin 2024). Ropes of varying size/diameter and composition were placed between baleen plate sections, simulating entanglement, and flow at varying speeds was recorded via a submerged, illuminated borescope camera or a camera placed outside the flume’s viewing window (Fig. 2B,E,F). Buoyant particles or colored dyes were added to resolve flow speeds and directions in video recordings (Werth 2013).

A new flow device (Fig. 2A) was constructed for this project based loosely on descriptions provided by Mayo et al. (2001). This involved a barrel tube with a large (~ 90 l) reservoir in which a section of 30 regular, full (~4 m) NARW or bowhead plates could be submerged, with a square 15 x 15 cm plastic inlet tube providing incurrent flow from a water tap at approximately 12 l/min. A clear viewing window allowed access to visualize water flow, and a hole in the inlet tube’s top enabled an illuminated borescope camera to be introduced for recording in different views relative to water flow. As with the other flow device, ropes or other lines were placed between baleen plates or pulled plates to the side to simulate entanglement within an actual whale mouth. Video recordings from both flow devices allowed analysis of alteration of flow parameters in cases simulating a normal baleen filter versus an entangled one.

Additional experiments involved pulling ropes entangled within baleen plates, with the distal end of the rope attached to a force transducer, so that the tensile forces needed to overcome friction of entanglement (Knowlton et al. 2012, 2016) could be recorded as ropes were pulled free (Fig. 2D). This yielded information regarding differences related to rope size and composition. The objective was to determine the ease or difficulty in firmly lodging or dislodging differently sized ropes, and those constructed with different materials such as cotton or plastic, between plates of the baleen filter.

CFD simulations were arranged and generated by the lab of Dr. Jean Potvin of the Department of Physics at Saint Louis University. Trials were run simulating regular full racks of NARW baleen, plus conditions in which one or two plates were missing or spread apart by an entangling line (simulating narrow and wide gaps), in varying locations within the mouth (=anterior, central, or posterior locations within a full baleen rack), so that in there were similar gaps in all cases. These trials documented alterations in flow speed and pressure at the site of the gap, as well as “upstream” and “downstream.” Additional opposing trials were conducted with blockages, rather than gaps, filling spaces between two or three adjacent plates (simulating a wide rope or attached gear blocking flow), and again, changes in pressure and flow speed were documented.

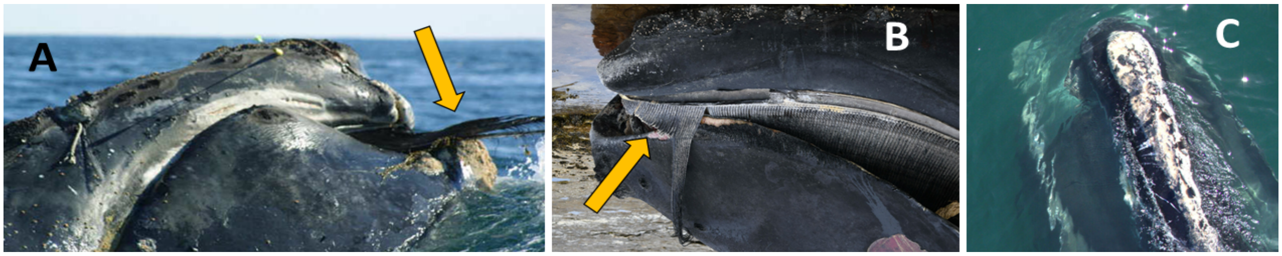


Figure 3. Examples of severe and permanent damage to multiple plates of NARW baleen due to gear entanglement. In A, bent plates project outside the mouth above the lower lip. In B, numerous broken plates near the anterior of the left rack are much shorter than normal. C shows a scarred rostrum and bent or missing plates following the removal of entangling gear.

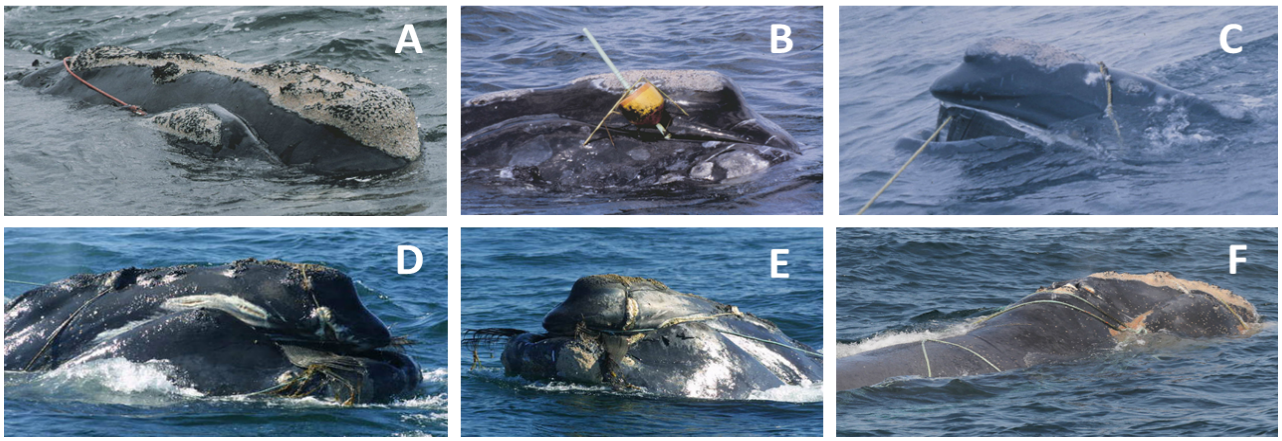


Figure 4. Examples of entangled NARWs showing varying degrees of entanglement in live whales, with one or more lines (and associated floats or other gear) entangled near the anterior, middle, and/or posterior of baleen racks, along with entangling the whale's torso and other body parts such as flippers and flukes.

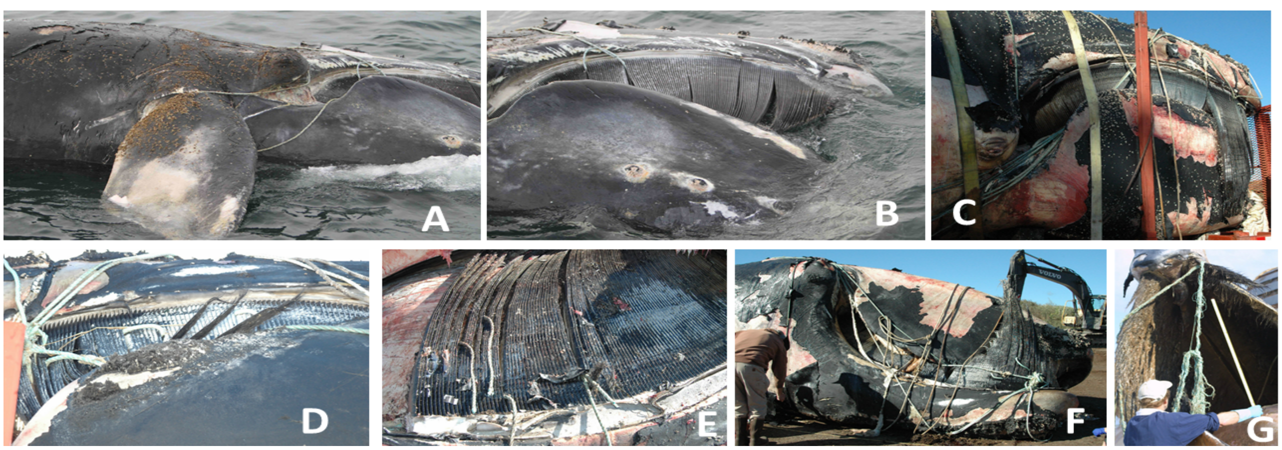


Figure 5. Examples of postmortem photos of NARWs found dead with entangling lines and gear, showing the scope of entanglement and fatal damage to whales' baleen and bodies.

## Results

Although we continue to collect and analyze data, to this point some interesting findings have been suggested or revealed.

First, photographs, video recordings, aerial and shipboard observations, and other accounts of living whales confirm that entanglement is a serious threat that occurs frequently in NARWs (Figs. 3-5), along with other baleen whale species, especially humpback whales (*Megaptera novaeangliae*). Our database survey confirmed that 1) many individual whales remain entangled for long periods, 2) some whales suffer more than one entanglement event over the course of their lifetimes, and 3) many deceased whales either are entangled at the time of death or exhibit scars from previous entanglement (Robbins et al. 2015). Together, our findings reiterate the general claim that entanglement is a leading cause of death for NARW and other mysticete species (Fig. 5), as previous studies (Johnson et al. 2005, Cassoff et al. 2011, Moore and van der Hoop 2012, van der Hoop et al. 2013, 2016, 2017a, 2017b, Moore et al. 2021, Knowlton et al. 2012, 2022, Reed et al. 2024, Crum et al. 2025) have documented.

Our study further revealed that oral entanglement of North Atlantic right whales (NARWs) may involve single or multiple lines/ropes as well as associated gear, including buoys, lodged in one or more (i.e., anterior, central, and posterior) regions of a baleen rack (Figs. 3-5). Lines typically protrude bilaterally (i.e., through both sides of the mouth at the same time), producing one or more gaps of varying size (narrow or wide), position within the mouth, and duration.

Interestingly, and somewhat unexpectedly, we observed, in video recorded sequences of unentangled NARWs feeding normally, evident gaps between plates of baleen that are small (usually about 3-5 cm) and presumably temporary (typically lasting just a few seconds). Such transient occurrences in living whales (Fig. 6) do not appear to be common, yet their occasional observation and frequency (showing up in ~8-10% of clips of feeding whales) suggest they are probably not rare. These gaps appear to be wholly unrelated to any current or previous entanglement event. Although their etiology is unknown, they are likely caused by normal flow of water accompanying typical filtration events. As quickly as these momentary gaps in baleen racks appear, they disappear, and they seem not to leave lasting adverse effects, either structurally or functionally (i.e., in terms of lasting physical damage or filtration dynamics). In brief, because hydrated baleen is so flexibly pliant, plates appear to bend back into their normal resting position readily, with no obvious intervention from the whale, or from a human or other source.

## Discussion

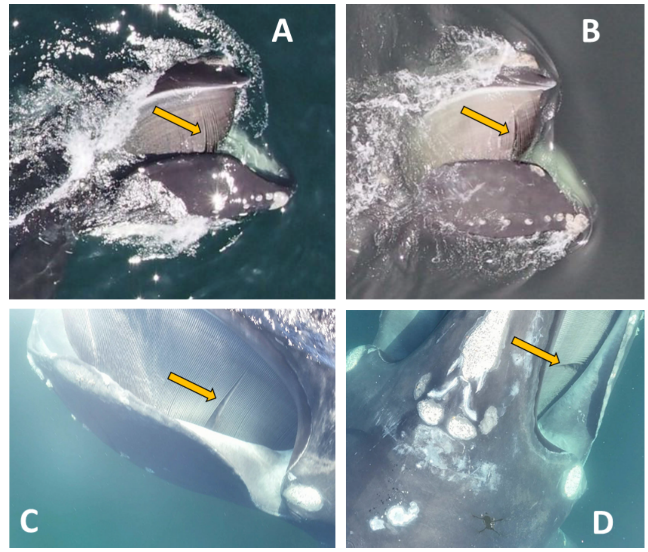


Figure 6. Sample images of minor gaps between plates of NARW baleen racks seen skim feeding near the surface. Based on video analysis, these gaps are likely unrelated to entanglement and are probably transient features that appear and rapidly (within 5-15 seconds) disappear with no known cause or resolution. Note reflection of aerial drone near bottom center of image D.

Overall, there is no question that entanglement is a crucial concern for all mysticetes but especially for NARWs and humpback whales. These species commonly swim and filter feed in coastal habitats where humans widely use fishing gear, including nets placed throughout the water column and traps or pots resting on the bottom but connected to surface buoys. Necropsy reports and photos clearly reveal the extent of the entanglement problem for whales, as has been documented in detail by numerous previous studies (Johnson et al. 2005; Cassoff et al. 2011; Moore and van der Hoop 2012; van der Hoop et al. 2013, 2016, 2017a, 2017b; Moore et al. 2021; Knowlton et al. 2012, 2022; Reed et al. 2024; Crum et al. 2025). Entanglement undoubtedly remains a major source of mysticete morbidity and mortality.

As noted in the preceding section, we found that small, temporary gaps within the baleen filter of mysticetes occur frequently and by all indications result from normal/natural filtration behavior (Fig. 6). Preliminary review of filtration in multiple mysticete species suggests these fleeting gaps may occur in all baleen whales, but they appear to be especially common in the notably large oral filters created by the exceptionally long (3-4+ m) baleen plates of balaenid (bowhead and right) whales. We believe that the incidence of such small gaps has heretofore been unappreciated or entirely unobserved. This is another instance where recent improvements in close-range UAV drone photography are revealing previously unknown aspects of whale morphology and behavior (Werth et al. 2019). Nonetheless, we believe that these small, transient gaps in the baleen filter pose no immediate or lasting threat to whale health or filtration.

However, if baleen is damaged, deformed, or bound in an improper position for considerable time, the prognosis is not so rosy. Our results suggest that that lasting damage generally occurs after baleen remains bent for 5-10 days. In such cases, the baleen may return to a position close to its prior form, yet it will likely show permanent deformation (i.e., leaving gaps or breaks within a full baleen rack). Thus, even if entangling lines or gear are removed from an entangled whale, we contend that there very likely will be lasting negative consequences. Results from our physical experiments and computer simulations further indicate that this structural deformation very likely adversely affects the flow regime underlying filter feeding (Werth 2004; Werth et al. 2016b; Werth and Potvin 2024). Specifically, and importantly, we have found that much of the effect involves altered flow not only through this point source, but also in regions of the baleen filter far from the altered morphology. Our data indicate that flow alterations occur both “upstream” and “downstream” from the filled or widened gap, the former created by a line remaining between baleen plates and the latter created by the line’s eventual removal. Further, the upstream and downstream effects are quite different.

During normal mysticete filtration, water passes through intraplate gaps (spaces between adjacent plates), which are typically average about one cm in width (range 6-12 mm). This involves laterally-directed movement of water from the center of the mouth and in the gaps between plates toward the exterior, such that it constitutes throughput filtration via perpendicular flow. However, the predominant flow during continuous (steady state) filtration in balaenid (bowhead and right) whales is tangential (crossflow) filtration, in which most of the water flows along or parallel to the filter rather than perpendicularly through it (Werth and Potvin 2016; Potvin and Werth 2017, 2024). Eventually, water inside the mouth flows outward between plates, but this generally occurs near the posterior-most side of the filter (Fig. 1). The extent to which humpbacks and other whale species also use crossflow filtration is unknown (Werth and Potvin 2024), but it may be significant; in any case, whether most flow is perpendicular or tangential, and even if the primary filtration is not sieve-like (Werth 2013; Werth et al. 2018a, 2018b), eventually water within the mouth flows out between baleen plates. In short, flow between baleen plates is ultimately what mysticete filtration is all about. Thus, anything that influences this outward flow can affect filtration. Until the current study, what was unappreciated was the extent to which flow dynamics can be affected a considerable distance from the site of the blockage or gap. This is a novel and unexpected finding, and potentially a significant one, because it suggests that even minor entanglements might have major global consequences for baleen filtration.

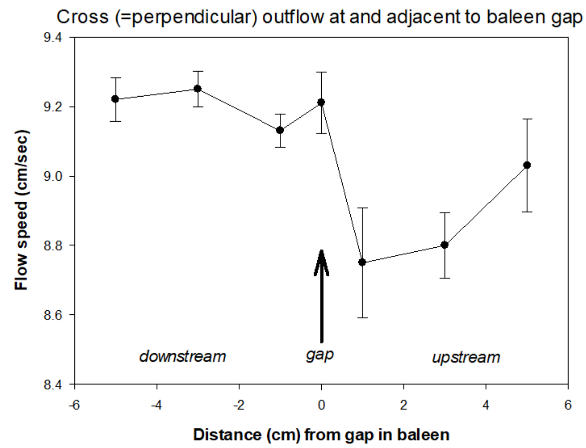


Figure 7. Results from flow tank experiments show that cross (=perpendicular) water flow through NARW baleen (of 25 full size plates) increases through a 2.5 cm gap equivalent to the absence or bending of two baleen plate, compared to the same flow upstream, where all baleen plates are spaced normally (i.e., with no gaps or damage). Furthermore, cross flow immediately upstream of the gap is diminished, whereas cross flow downstream of the gap remains elevated.

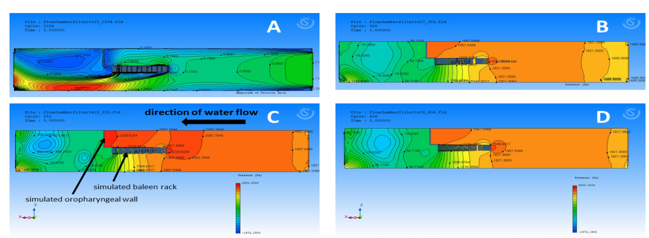


Figure 8. CFD flow simulations, with water flowing from right to left in these schematic dorsal views, show differential pressure effects of wide (2-3 plates missing) gaps in the posterior of a baleen rack, closer to the oropharynx (image A), or in the anterior of a rack, farther from the oropharynx (B), or with a narrow (1 plate) gap in the posterior (C) or anterior (D) of the baleen rack. Warmer colors indicate higher pressures; cooler colors indicate lower pressures.

Flow tank experiments using pieces of actual baleen tissue indicate that water passes through enlarged gaps between baleen plates faster than it does during normal intra-plate flow (Fig. 7). In other words, perpendicular flow is stronger through an enlarged gap, as would be created by the lasting effect from a prior entanglement. Likewise, computational fluid dynamics trials simulating flow through gaps of varying width confirm the findings of our flow tank experiments—namely, that flow increases through widened gaps (Fig. 8). However, experiments and CFD trials both reveal that crossflow is altered not only at the immediate location of the gap but also "upstream" and "downstream" of the gap (i.e., anteriorly and posteriorly to it, or closer to the front and back of the mouth). Specifically, there appears to be a notable (30-40%) decrease in flow pressure and velocity upstream of any unusual gap of any size (i.e., closer to the front of the mouth), and a corresponding increase in flow pressure and velocity downstream of a gap (closer to the back of the mouth). Again, this suggests that an entanglement affecting just one of the 300 or so gaps within a baleen rack might presumably alter flow between the plates, depending on where in the rack the entanglement occurs.

If a previous entangling line creates a gap, more water would escape there. Provided there is a normal mat of baleen fringes medial to this gap (closer to the tongue and center of the mouth), more prey items would collect there. Again, the atypically widened gap is also important in that it reduces intragap flow anterior to the gap; closer to the front of the mouth, there might be less suction, and thus fewer particles collecting on the mat there. Downstream of the widened gap, closer to the back of the mouth, intragap flow is stronger. One conclusion is that the closer to the front of the mouth the entangling line occurs, the less damage is done. If one or more entangling lines firmly lodge between plates (and create eventual gaps once removed) in the posterior region of the rack, then potentially the entire rack loses filtration ability and its collection performance would be compromised, especially if the medial fringe mat is notably affected. The more the fringe mat maintains integrity, the better the filtering and accumulation of prey particles throughout the entire rack. But in practical terms, a widened gap in the filter means prey-laden water flows more slowly through any of the baleen rack anterior to ("ahead of") the gap, whereas it flows faster posterior to ("behind") the gap. Due to overall flow conditions, fewer prey particles are likely to be captured ahead of the gap and more may be captured behind it.

Research is ongoing to determine precise flow effects created by blockages (as from entangled lines in place) in addition to widened gaps created by removal of entangled lines, but the simple, immediate answer is that just like atypical gaps between baleen plates, atypical blockages (absence of usual gaps) also alter normal flow dynamics. Further, they appear to do so not only in the immediate location of the altered morphology but also throughout the entire rack.

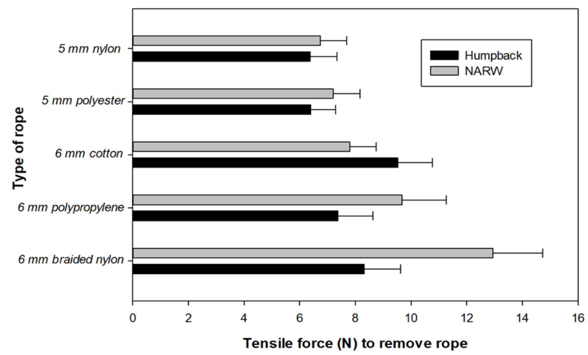


Figure 9. Results from experiments to remove various lines lodged between baleen plates.

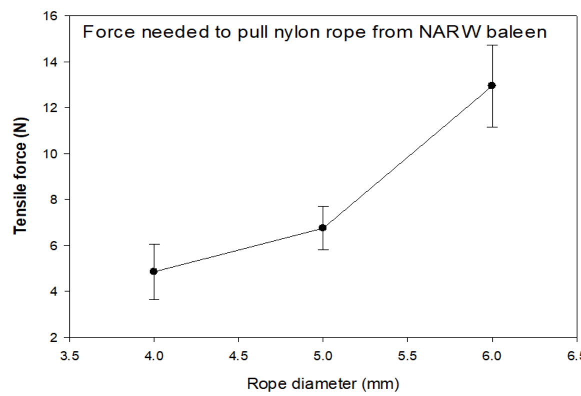


Figure 10. The wider an entangled line, the more difficult it is to disentangle it.

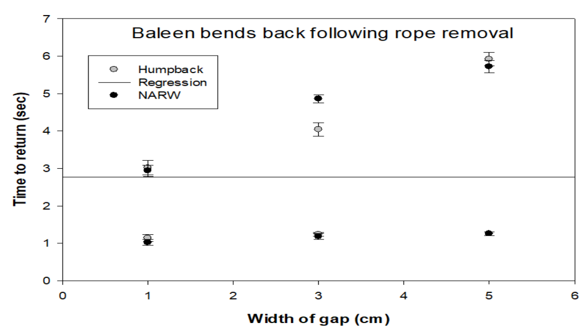


Figure 11. If an entangled line is removed within minutes of entanglement, the baleen rapidly returns (within seconds) to its original position, but recovery speed also depends on the size of the entangling line. Upper data points indicate experiments using dried baleen, which takes longer to recover; wetted baleen (lower data) recovers much more quickly (Werth et al. 2016a).

In addition to this factor of entanglement location, there is also the question of time, in terms of how long an entanglement lasts before it is resolved, either naturally or via anthropogenic interventions (Figs. 9-11). This determines the severity of altered flow dynamics, and hence foraging efficiency (i.e., ability to capture prey).

As discussed previously, even once an entangled line is removed, plates might be spaced farther apart than normal if the line was sufficiently large in diameter and/or if the entangling line was in place long enough to do lasting damage by bending plates out of their normal position. However, if the entanglement is quickly resolved (again, naturally or by humans), the baleen can probably recover its normal shape and filtration ability with little or no lasting damage. Review of underwater video clips of filtering whales show that slight gaps are not unusual, and that they "heal" themselves with no apparent harm done (Fig. 6). Likewise, individual or clustered plates of bowhead or right whales that stick entirely outside the mouth's lower lip are not uncommon, but they appear to "pop" back into place, apparently quickly and easily, without intervention. Underwater sequences in which multiple transient gaps in baleen racks briefly appear and disappear are encouraging. They suggest that spacing of plates is both variable and not as important as widely presumed and confirm that baleen plates and rubbery gingival zwischensubstanz frequently absorb and recover from many stresses they encounter.

In other words, there is "good news" in that baleen is highly flexible and readily bends back into position, but the corresponding "bad news" is that there is a limited time frame for baleen to "bounce back." If baleen is bent for a sufficiently long period, probably on the order of weeks, it is unlikely to ever bend back into its original position. There will be lasting damage to the structure of the keratinous oral filter (Werth 2017) and corresponding damage evident in the filter's function due to an altered flow regime (Werth and Potvin 2024). Relative to an undamaged baleen rack, part of the damaged rack (anterior to the gap) will receive comparatively less flow than normal whereas another part (posterior to the gap) will receive more flow. The portion with less flow will likely collect fewer prey items or otherwise operate with decreased capture efficiency.

Therefore, it appears that both the *duration* and the *location* of oral entanglement have major functional consequences, with both factors determining the extent of the potential harm to filtration. A third crucial variable affecting the functional impact of fishing gear or other line entanglement in baleen whales is the *size* of the gap. The wider the gap, the faster the flow through it *and* the greater the disruption of upstream and downstream flow.

Together, these three factors (size, duration, and location) are key determinants of the immediate and lasting effects of oral entanglement on flow through the baleen filter, and thus the success or failure of filtration relative to normal, unimpaired filter feeding.

Many questions remain to be addressed, such as how all of these flow alterations affect basic aspects of filtration, including (notably) drag forces. This is a major focus of ongoing work.

We emphasize that this study remains a work in progress, with all three aspects of data collection and analysis (review of entanglements documented by photographs, video recordings, and descriptive narratives; physical experiments with flow tanks; and computational flow simulations) ongoing. Cooperative collaboration also continues among outside (non-Hampden-Sydney) scientists providing data and expertise. This project may therefore yield additional notable findings in the future. The eventual goal remains to present results at one or more major conferences and to publish the results in peer-reviewed journal articles.

## Conclusion

Even minor or brief entanglements anywhere on a whale's body, even those not involving the mouth, will have severe repercussions for feeding. Obviously, entanglement generally impedes locomotion or breathing, affecting whales' energetics and metabolism and creating physical, physiological, and psychological stress, thereby adversely impacting key factors in foraging, especially locating and capturing sufficient quantities of prey and hence whales' caloric intake. Our primary objective is to address numerous basic questions regarding the effects of oral entanglement on filter feeding in whales. How serious a problem is entanglement for right whales and other mysticete species? To a great extent, we already know the simple and obvious answer to this question. Entanglement is a major cause of mortality for baleen whales.

While acknowledging such crucial and common effects, this ongoing study instead focuses specifically on the direct consequences of oral entanglement on filter feeding, including the impact of oral entanglement on the structure and growth of the baleen filtering apparatus and its component tissues, and on the fluid dynamics of water flow during filtration. Must all entanglements be lethal or cause serious harm if they are resolved sufficiently quickly, with or without human intervention? Is there lasting damage from even brief and minor entanglement? How many plates must be involved, and for how long, to incur significant damage? Where in the mouth does entanglement typically occur? Does an entanglement's location matter, and if so, how? What kinds of effects does entanglement have on baleen, such as temporary or permanent bending of plates, creation of gaps between plates, plate breakage, or damage to the gingiva where baleen grows (Werth et al. 2020, 2021)? Further, to what extent do these types of damage have lasting effects even after removal of entangling ropes, nets, buoys, or other gear? How do all of these varying types of damage potentially affect fluid dynamics of the baleen filter, and hence a whale's caloric intake? In short, how much trauma is too much for a whale to overcome? In general, how seriously does entanglement affect baleen's role in filter feeding?

In brief, our findings provide novel and important answers to these basic questions. Flow, and thus filter feeding, appears to be altered at the immediate site of an entangling rope that is present or, even after removal, has been in place long enough to bend baleen permanently. Global flow effects likely affect the entire mouth, and these may be substantial, particularly for lines entangled near the posterior region of the mouth. The more entangling lines there are, or the larger they are and the longer they remain entangled in the mouth, the worse the damage. That much is unsurprising, but what was unexpected is that even after lines and gear were removed, they likely had lasting negative effects. Our work adds to the growing body of research clearly demonstrating that entanglement is one of the most serious threats to the health and mortality of whale populations, particularly those (like NARWs) that live and feed in heavily fished coastal waters (Knowlton et al. 2012; Borggard et al. 2017; Dolman and Brakes 2018; Seary et al. 2022). Our findings add renewed impetus for fishers, policymakers, and conservationists/management specialists to continue research on "ropeless" traps deployed and retrieved without attached lines permanently spanning the water column (Howle et al. 2019; Moore 2019; Myers et al. 2019; Lambert 2023).

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