MARINE MAMMAL SCIENCE, 22(2): 299–310 (April 2006)

DOI: 10.1111/j.1748-7692.2006.00020.x

EXPERIMENTAL MODELING OF LARGE WHALE ENTANGLEMENT INJURIES

BECKY L. WOODWARD
Mechanical Engineering Department,
University of Maine,
Orono, Maine 04469, U.S.A.
E-mail: woodward_becky@yahoo.com

JEREMY P. WINN
School of Marine Sciences,
University of Maine,
Orono, Maine 04469, U.S.A.

MICHAEL J. MOORE
Biology Department,
Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts 02543, U.S.A.

MICHAEL L. PETERSON
Mechanical Engineering Department,
University of Maine,
Orono, Maine 04469, U.S.A.

ABSTRACT

The abrasive impact of commercial fishing gear on right whale fluke tissue was modeled using a reciprocating load generator. A line passing over the leading edge of a fluke specimen was fixed at one end while the other end was loaded in an oscillatory manner. A 24-h abrasion test using an accelerated loading rate of 60 cycles/min and a 9.0-kg load on the fixed end of the most abrasive line tested (old sink line) was used to simulate a whale swimming 2 m/s towing four standard lobster buoys for five days. A tension load of 267 N was generated on the oscillatory side of the fluke. The test line failed to break the skin on the fluke but, instead, produced a compression furrow (maximum depth 0.31 cm) that closely resembled marks found on stranded right (*Eubalaena glacialis*) and humpback (*Megaptera novaeangliae*) whales. Different line types (float *vs*. sink) and ages of rope (new *vs.* old) produced furrows of varying depths and appearances. Further tests characterizing whale skin/fishing line interactions will provide a better understanding of the mechanisms that govern entanglement injuries and provide a framework for better forensic analysis and interpretation of gear-related injuries observed in large whales.

Key words: modeling, entanglement, injury, cetacean, right whale, *Eubalaena glacialis*, humpback whale, *Megaptera novaeangliae*.

In recent decades, many of the serious injuries and mortalities in large whales are a direct result of marine industrial activities, especially commercial fishing and shipping (Wiley *et al.* 1995, Knowlton and Kraus 2001). Entanglement in fishing gear is cited as the most frequent cause of injury and death in the Atlantic humpback (*Megaptera novaeangliae*) population (Wiley *et al.* 1995, Barco *et al.* 2002). Between 1997 and 1999, 88% of the humpbacks photographed showed scars indicative of entanglements around the caudal peduncle (Robbins and Mattila 2000).

Likewise, entanglement affects the North Atlantic right whale (*Eubalaena glacialis*). Kraus (1990) reported that 57% of the cataloged right whale population had entanglement scars on the peduncle. A more recent scarification analysis evaluating all regions of the body for whales photographed between 1980 and 2002 raised the estimate to 75% of the animals having been entangled at least once, with serious injuries including fatal and potentially fatal entanglements on the rise (Knowlton *et al.* 2005). Four of 54 documented right whale deaths between 1970 and 2002 were confirmed to be the result of an entanglement in commercial fishing gear (Moore *et al.* 2005). Many entangled whales become emaciated due to the increased energy cost of swimming and impaired feeding ability caused by the entangling gear (Knowlton and Kraus 2001). The emaciated carcasses sink when the animals die due to the loss of the buoyant blubber layer and are not recovered (Moore *et al.* 2005). As such, it is likely that the number of entanglement mortalities has previously been underestimated (Knowlton and Kraus 2001). With as few as 300–350 animals remaining and a declining population growth rate, the reduction of human-induced mortalities is of utmost importance to the viability of the critically endangered North Atlantic right whale population (Caswell *et al.* 1999).

Fishing gear modifications such as weak links have been introduced into the commercial fishing industry in an effort to reduce entanglement risks (Kozuck *et al.* 2003), yet the factors that govern a rope-induced injury have not been characterized. Analysis of entangling lines and the resultant tissue damage to the animal is difficult to assess on a live whale at sea. Stranded animals offer an alternative for examining rope-induced injuries, but often the entangling gear has been removed by the gear owner before an in-depth analysis of the entanglement can be made (Moore *et al.* 2005).

A controlled, systematic means of examining line type, line tension, duration of contact, and the resultant tissue damage is necessary to create an unbiased characterization of the interaction between whale skin and fishing gear. Such data would prove useful in forensic analysis of rope marks found on stranded animals, as well as evaluation of the effectiveness of proposed gear modifications for reducing the risk of serious entanglement injuries. To address this need, a reciprocating load generator was designed, fabricated, and tested as a means of experimentally producing compression furrows in the skin similar to those commonly seen in entangled animals.

Methods

A reciprocating load generator (Fig. 1) was used to characterize the abrasive impact of different types of commercial fishing gear on the tissues of a right whale fluke. The experimental test system was designed to model an entanglement scenario where one end of the entangling line is fixed and the other end is loaded in an oscillatory manner (*i.e.*, a line wrapped about the base of the flipper trailing back to the flukes where the up and down motion of the tail alternately loads and relaxes tension on

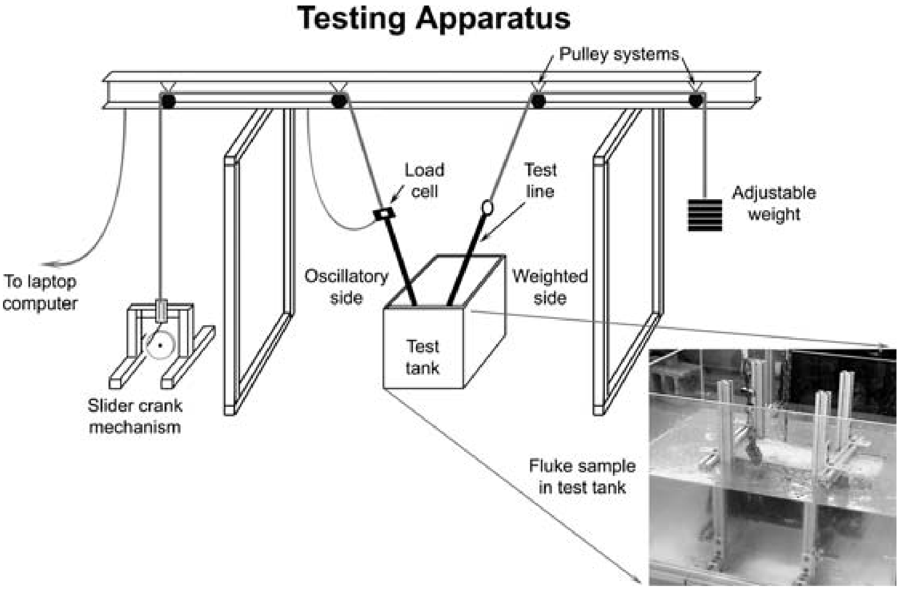

Figure 1. Reciprocating load generator test bed for abrasive impact testing. Slider crank mechanism on the left converts rotary motion of the motor into cyclical tensioning and relaxation of test line wrapped around leading edge of fluke specimen. Adjustable weights create tension in the test system and fix the line on the weighted side of the sample. The load cell measures the tension on the line on the oscillatory side of the fluke. Tests were conducted with the fluke specimen submerged in a small, static seawater tank (inset).

the line). The system uses a slider crank mechanism connected to a $^1/_4$-hp, 62-rpm gear motor (Model 6ML51, Dayton Electric Manufacturing Company, Lincolnshire, IL) to convert the motor's rotary motion into a cyclical tensioning and relaxation of a line wrapped over the leading edge of a fluke specimen.

Accelerated testing is often used in the characterization of wear rates and abrasive impacts in material characterization studies. These tests allow long-term effects to be observed in a condensed time period. For this study, all abrasive tests were performed at an accelerated rate with a motor speed of 60 rpm. The average fluke stroke rate for a right whale is reported to be approximately 12 strokes/min (Nowacek *et al*. 2001). Thus, the tests were conducted at five times the normal fluke stroke rate of the animal. The results of an accelerated 1-h test would therefore be indicative of the amount of abrasion the animal would experience during five hours of normal swimming.

Abrasive testing of biopolymers such as skin with the polymeric fishing gear is rate dependent (Fung 1981). Pressure, velocity, and temperature all affect wear rates of one surface against another. The pressure of the test line and the velocity of its motion were fixed throughout the test by the speed of the motor and the weights applied to the fixed end of the test line. To dissipate heat generated during the accelerated test process, the fluke specimen was secured in a small 89-cm long × 64-cm wide × 61-cm deep static seawater test tank using an adjustable clamping system bolted to the bottom of the tank. The test tank was filled with 12.5°C seawater until the fluke sample was completely submerged. The underwater testing simulated the frictional line effects a whale might experience in an actual entanglement situation.

A 2.74 m × 1.22 m × 1.52 m test frame was rigged using an 11-mm polypropylene/polyester blend commercial sink line. A 3-m length of rigging line ran from the slider crank mechanism over a series of pulleys to an MLP-100 load cell tensiometer (Transducer Techniques, Temecula, CA) which measured the tension in the line between the fluke specimen and the motor during the abrasive testing. The signal from the load cell ran through a TMO-1 amplifier/conditioner module (Transducer Techniques, Temecula, CA) and was recorded *via* a serial port on a laptop computer.

A 1.4-m sample of each of the selected test lines was inserted in the test rig and ran from the load cell, down into the test tank, around the fluke sample and up to a carabiner on the far side (Fig. 1 inset). A second 3.5-m length of the 11-mm rigging line ran from the carabiner on the test line back over a second series of pulleys to a set of dead weights hanging on the opposite end of the frame. Weights were added or removed to achieve the desired tension in the test line. The weights essentially fixed the line in place on the side of the sample nearest to them (the weighted side of the sample). As the motor turned, the slider crank mechanism traveled over a 10-cm throw, pulling on the rope on the oscillatory side of the fluke (left side in Fig. 1) and alternately causing the line to go taut and then slack. Contact length of the test line with the fluke sample was approximately 38 cm.

Abrasive tests were conducted using 9.5-mm diameter line commonly used in commercial fixed gear fisheries in Maine[1] and Massachusetts (McKirenan *et al*. 2002). Both polypropylene float and polypropylene/polyester blend sink lines were tested, including new and used samples of each type of rope (Fig. 2). Rope samples designated as "old" were obtained from a local lobster fishery (Southwest Lobster and Fish Unlimited, Southwest Harbor, ME). Old lines had been previously used for lobstering and contained ingrained mud and fraying rope fibers. All samples were of a three-strand twisted construction.

A 48-cm-long fluke specimen was obtained from the leading edge of the left fluke lobe of stranded right whale NEAq Eg 1004. The sample had a 20-cm dorsal–ventral thickness and a 20-cm anterior–posterior depth. The 16-m-long whale carcass from which the sample was taken had been floating in the ocean for approximately four to seven days in 4°C seawater before it came ashore.[2] The post-mortem rate of skin loss in cetaceans is quite variable, and despite the significant time period between the animal's death and the collection of the specimen, the epidermis remained well adhered to the underlying tissues of the fluke. The fluke sample was bagged in the field to minimize the risk of being waterlogged, and then placed on ice in a cooler during its four-day transport period back to the lab facility where it was frozen. Prior to the abrasive testing, the fluke specimen was held at 4°C in a cold room for 60 h until it was fully thawed.

Individual test sites on the fluke sample were separated from each other by a distance of 2 cm. Initial comparative line tests for new and old, float and sink lines were run for a period of one hour with 4.5 kg of dead weight applied to the system. A previous in-house drag test conducted in the University of Maine's tow tank facility indicated that a standard (15 cm diameter, 36-cm long) lobster buoy towed underwater at a speed of 2 m/s produced 22 N of drag. The buoy was attached to a tow bar 0.7 m below the water surface by a 0.5-m length of 9.5-mm line. Drag forces were measured

[1] Personal communication from Stephen Robbins, Gear Technologist, Maine Department of Marine Resources, Boothbay Region, West Boothbay Harbor, ME, 11 July 2005.

[2] Campbell-Malone, R., M. Moore, W. A. McLellan and S. Barco. 2004. Draft large whale necropsy report. *Eubalaena glacialis.* Field number VMSM20041004. Nags Head, NC, 30 February 2004.

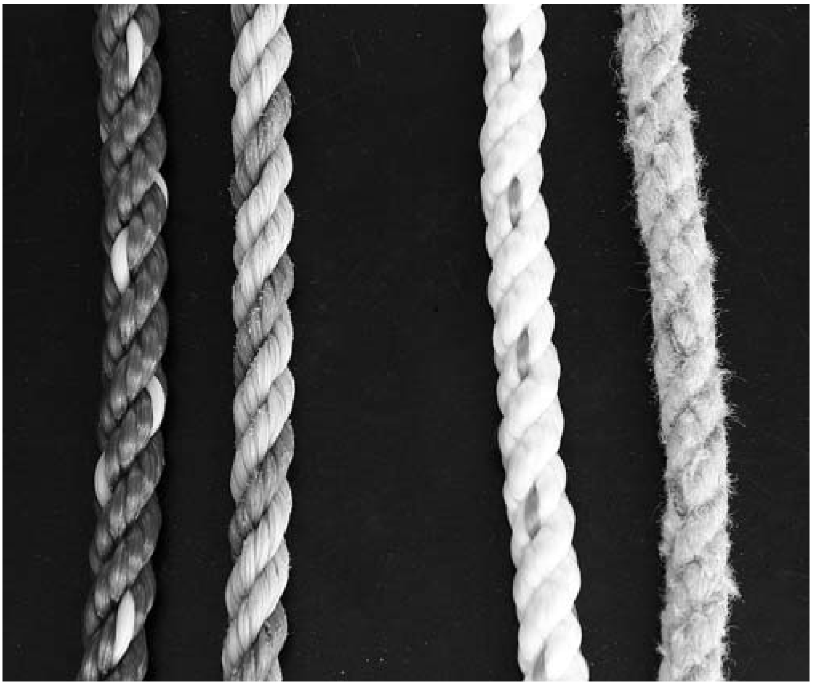

Figure 2. Rope samples, 9.5 mm in diameter, used during comparative line tests. From left to right: new float line, old float line, new sink line, old sink line. Old samples contain visibly fraying fibers.

by a load cell mounted on the tow carriage. A standard single, two-brick lobster trap produced 222 N of drag at the same 2-m/s tow speed.[3] For the abrasive testing, the 4.5-kg weight on the test system produced 44 N of tension in the test line on the weighted side of the specimen. This force was roughly equivalent to a whale towing two lobster buoys at a speed of 2 m/s, a tow speed well within the normal range of swim speeds for right whales (Nowacek *et al*. 2001).

The old sink line was selected as the most abrasive and additional testing was conducted with this test material. A 12-h comparative tension test was conducted by doubling the dead weight applied to the system from 4.5 to 9.0 kg to determine the effect of increasing tension in the test line. A comparative duration test was also conducted by applying 9.0 kg of dead weight to the system and doubling the run time from 12 to 24 h. All tests were conducted using the accelerated 60 strokes/min cycling rate.

Following the abrasive tests, the midline of the fluke edge was marked and designated as Position 0. Depth measurement stations were created every 3 cm down the curve of the fluke on either side of the midline for a total of seven measurement stations on either side of the fluke. Positions on the fluke were designated with positive numbers on the oscillatory side of the fluke and with negative numbers for the

[3] Personal communication from John Riley, Ph.D., School of Marine Sciences, University of Maine, Orono, ME 04469, 30 January 2004.

weighted side of the fluke. Depth measurements of the resultant furrows were taken to the nearest 0.25 mm at each of the measurement stations along the surface of the fluke using a pair of dial calipers.

Results

The fluke structure with its network of collagen fibers is quite flexible in both the spanwise and chordwise directions. Despite being firmly clamped on either side of the test site, the fluke sample as a whole showed a substantial degree of lateral deflection in response to the applied load. The bending and compliance of the sample helped dissipate the load on the line and mitigate its abrasive impact. As the testing progressed, the weighted end of the line embedded itself in the skin, remaining nearly stationary with only about a 1.6-mm movement with each loading cycle. The oscillatory end of the rope connected to the motor continued to move, causing the line to become taunt and go slack in a cyclic manner. This motion modeled the rubbing abrasion caused by a line that is fixed at one end but moving at the other, such as in a fluke entanglement of a large whale.

Figure 3 shows the marks produced on the fluke sample during the 1-h comparative line test using a 4.5-kg load and different types of fishing gear lines. Tension in the line on the oscillatory side of the fluke ranged from 173 to 227 N depending on the frictional coefficient of the different line types with the skin tissue.

The new and old samples of 9.5-mm-diameter commercial float and sink lines left noticeably different marks on the fluke sample. The slick, smooth new float and new sink lines were less abrasive than the same diameter of old samples with their frayed fibers and ingrained mud. Both new samples left visible marks on the skin, but did not create furrows of measurable depth, while both the old float and the old sink lines produced significant furrows in the epidermis.

Line type affected both the appearance and depth of the resulting mark on the skin. The new float line left a mark with visible vertical streaks, while the new sink line had more of a polished appearance. The float line was a much stiffer rope with clearly defined fibers within each of the three strands that formed the rope. The individual strands left marks on the skin as they moved back and forth, resulting in a streaked appearance. The sink line, on the other hand, had a more cottony appearance without prominent individual fibers. This resulted in a smoother, more polished mark on the skin (Fig. 3).

Both the old float and old sink samples caused a furrow of similar maximum depth ($\sim$0.17 cm) on the oscillatory side of the fluke. In both cases, the furrows clearly showed the three-stranded twist of the rope with ridges in the skin corresponding to the ridges on the rope. However, the furrow caused by the old float line had small diagonal breaks in the skin at each bump in the furrow (Fig. 4). These mini-cuts were caused by the frayed fibers on the old rope. The old sink line furrow had a smoother appearance and did not contain these mini-cuts. When looking at the depth of the furrow over the contact length of the rope, however, the deeper region of the sink line furrow was maintained over a longer contact length (Fig. 5a). As a result, the old sink line was determined to be the most abrasive and was used for additional comparative tension and longer-duration testing.

Increasing the tension on the test line affected the depth and length of the furrow created by the old sink line (Fig. 5b). A 4.5-kg dead weight produced a maximum of 173 N of tension in the line on the oscillatory side of the fluke. Increasing the dead weight to 9.0 kg increased the tension on the oscillatory side to a maximum of 267 N. As would be expected, the maximum depth of furrow caused by the 9.0-kg weight

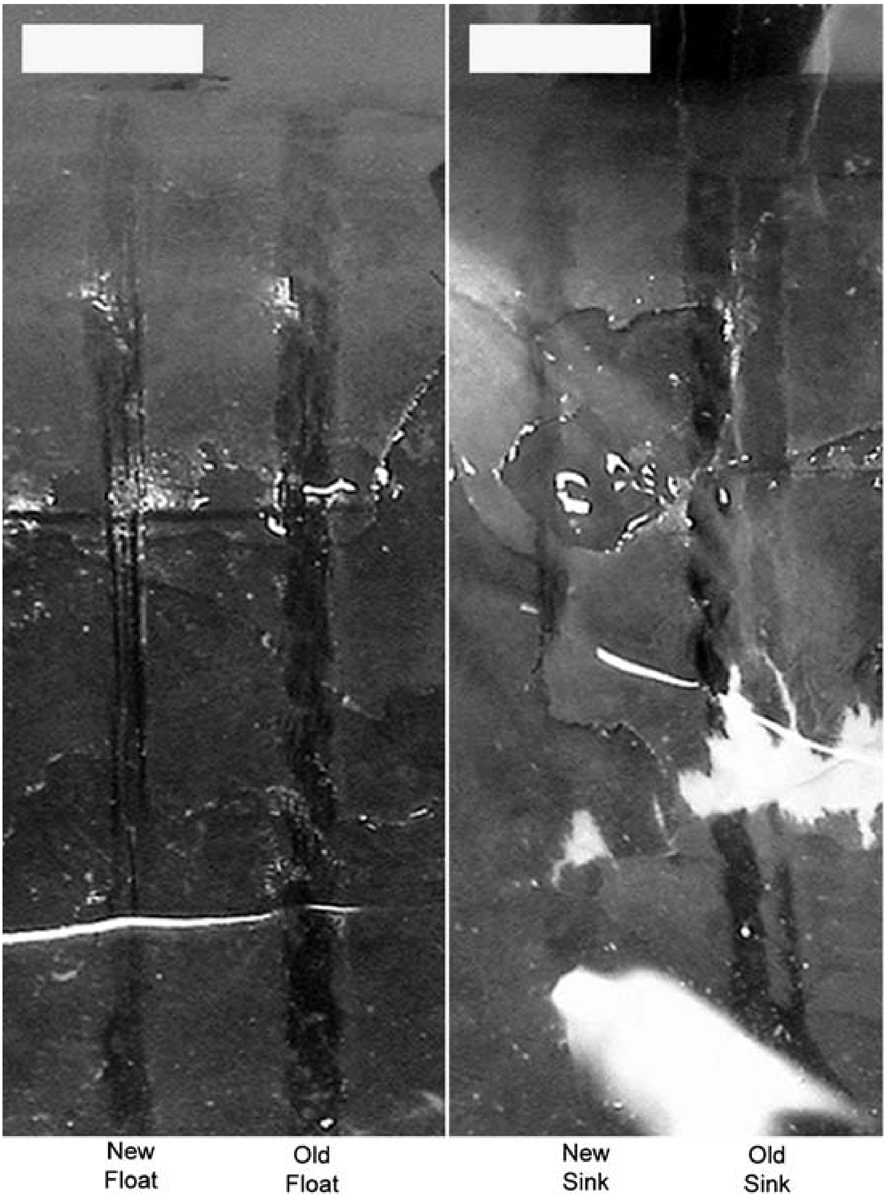

Figure 3. Experimentally induced furrows on the oscillatory side of the fluke generated during the comparative line test. Test was conducted using a 4.5-kg dead weight and loading rate of 60 cycles/min for one hour. Scale bars at the top represent 2.5 cm.

during the 12-h test was deeper than that of the same test conducted with the 4.5-kg weight (0.40 cm *vs.* 0.27 cm). The length of the resultant furrow also changed. With the 4.5-kg weight, the majority of the furrow was concentrated on the oscillatory side of the fluke. As the weight increased to 9.0 kg, the furrow extended onto the weighted side of the sample creating a longer, more evenly distributed furrow.

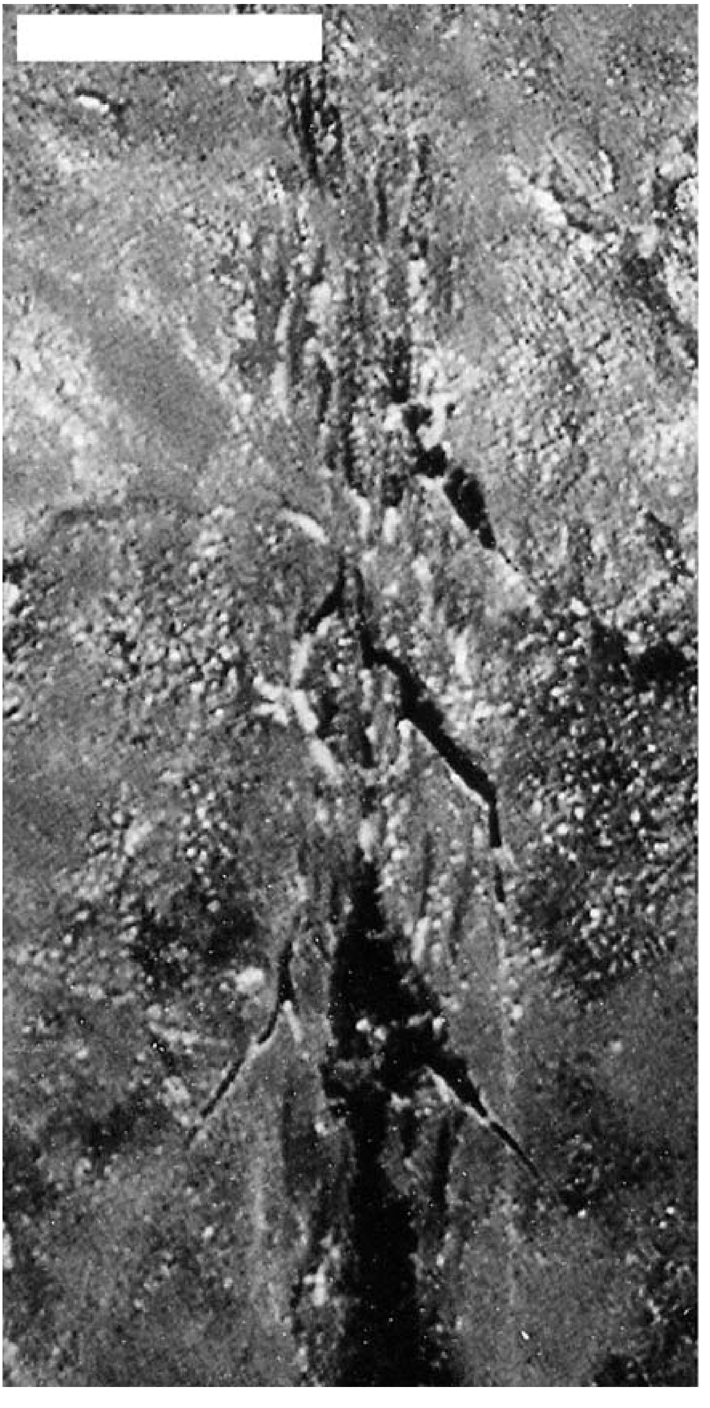

Figure 4. Mini-cuts found in compression furrow produced by 9.5-mm old float line during a 1-h test using a 4.5-kg dead weight and loading rate of 60 cycles/min. Scale bar represents 1 cm.

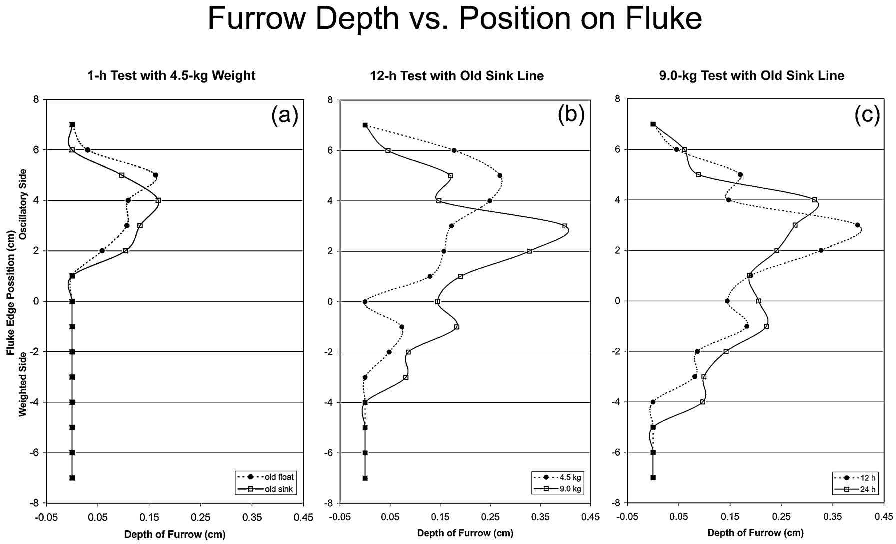

Figure 5. Furrow depth *vs.* position on the fluke for abrasive testing: (a) comparative line test with old float *vs.* old sink line, (b) comparative tension test with 4.5 kg *vs.* 9.0 kg of dead weight applied to the system, and (c) comparative duration test with 12- *vs.* 24-h test lengths. The oscillatory side of the fluke was designated as the one closest to the motor. The weighted side of the fluke was the one closest to the dead weight.

Extending the test duration also affected the character of the resultant furrow on the fluke (Fig. 5c). As the time length of the test increased from 12 to 24 h, the length of the furrow also increased. Interestingly, the maximum depth of the 12-h furrow was greater than that of the 24-h furrow (0.4 cm *vs.* 0.31 cm). However, the 24-h test produced a longer furrow with a greater overall furrow depth along its length.

Discussion

The test lines were unable to cut through the epidermis on the fluke sample during any of the abrasion tests conducted. It is not known if the post-mortem storage conditions of the fluke sample, first in cold sea water, then on ice, then frozen, and subsequently thawed, altered the durability of the fluke tissue. It was expected that the skin would quickly separate from the underlying tissues of the fluke sample during the abrasive testing. Surprisingly, the epidermis remained well adhered to the underlying tissues and provided a barrier of substantial strength. The final 24-h test using a 9.0-kg dead weight at an accelerated loading rate of 60 rpm was representative of the abrasion caused by a whale swimming at a speed of 2 m/s towing four standard lobster buoys for five days. Under a tension load of 267 N, the resultant compression furrow in the skin was only 0.31-cm deep.

Modeling of Entanglements

The experimentally induced furrows created during this study are quite similar in nature to those found on stranded whale carcasses that have been involved in an entanglement.

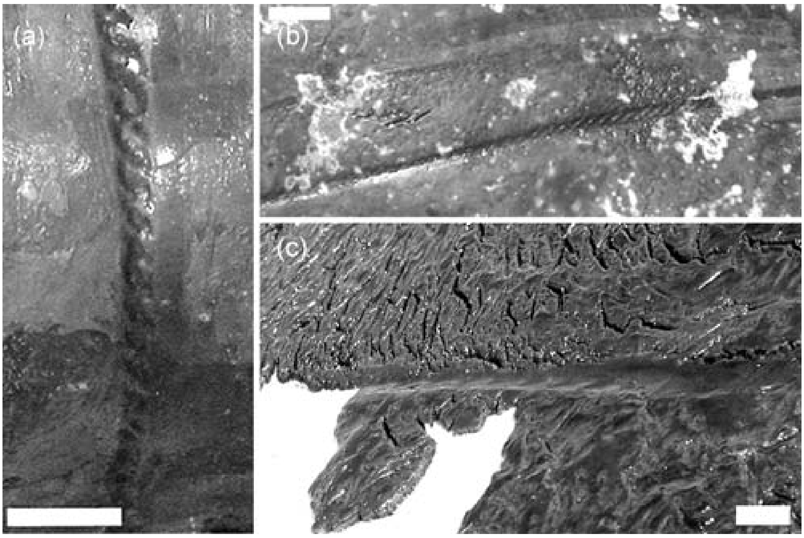

Figure 6. (a) Experimentally induced furrow from a 9.5-mm old sink line cycled at a rate of 60 rpm for 24 h using a 9.0-kg dead weight. (b) Scar on a humpback whale (CCSN 02–255 Mn) found dead in commercial lobster gear in 2002. (c) Scar on a right whale (NEAq Eg1238) washed ashore in 2001 after becoming entangled in a Danish seine. Scale bar in all pictures represents 3 cm. Photo credit (b) and (c) Scott Landry.

Figure 6 shows a comparison of the experimentally induced furrows on the right whale fluke and the scars found on humpback whale CCSN 02–255 Mn, which died as a result of entanglement in commercial lobster gear in 2002 (Moore, unpublished data). A similar mark was found on NEAq Eg 1238, a right whale that died as a result of an entanglement in a Danish seine (Moore *et al.* 2005). Even though the skin has separated from portions of the NEAq Eg 1238 carcass, the underlying tissues bear a groove of the same character.

The current test system provides a good model for recreating compression furrows on the skin tissues of a large whale fluke. However, a number of large whale entanglements have resulted in deep wounds that in some cases were lethal to the animal involved (Moore *et al.* 2005). Retooling and expansion of the current abrasion test system would allow penetrating wounds to be similarly modeled in an experimental setting.

Forensic Analysis

The results of this study indicate that the abrasive test system has the potential to aid in the forensic analysis of stranded whales that bear marks of entanglement. Careful examination of the marks on an entangled whale may help investigators determine which part of the gear was involved in an entanglement situation. A better understanding of the mechanisms involved in whale entanglements would help government agencies to make more informed decisions regarding fishing gear modifications and regulations.

To date, it has been difficult for necropsy teams to identify the type of gear involved in an entanglement unless some of the gear remained on the animal. Gear owners often remove entangling lines to avoid the negative ramifications associated with cetacean bycatch. In many cases, animals come ashore with only the resultant rope injuries, leaving researchers to puzzle out the type of gear involved and the nature of the entanglement.

A full experimental characterization of the furrows left by different line types under different loading conditions may allow necropsy teams to better identify gear types involved in an entanglement. The 1-h comparative line test showed that the furrows created by the commercial float and sink lines differed from one another. The new float line left vertical streaks in the furrow while the old float furrow contained mini-cuts at the ridges corresponding to the twists in the line. The sink line, on the other hand, overall produced a smoother furrow. The position of the rope marks on the animal's body may also provide clues about the loading on the entangling line. Experimental furrows were generally deeper on the oscillatory side of the fluke sample.

Further laboratory tests will increase the forensic value of the load generator for necropsy evaluations of entangled animals and could provide an atlas of the nature and timing of injuries attributable to specific rope types and entanglement scenarios. Additional controlled testing of impulse loads, additional line types, increased line tension, freshly dead and unfrozen fluke tissues, longer test durations, and varied load cycling rates will provide a means of characterizing whale skin/fishing line interactions so that the mechanics and severity of entanglement wounds can be better understood.

ACKNOWLEDGMENTS

This research was supported by the Mini-Grants Program at the National Fish and Wildlife Foundation. The authors would like to thank the members of the necropsy team involved in the case of NEAq Eg 1004, who made it possible to secure a fluke sample for the abrasive testing. The necropsy team members included individuals from the Virginia Marine Science Museum, UNC Wilmington, and Woods Hole Oceanographic Institution. The fluke sample was obtained under NMFS permit No. 932–1489–03/PRT009526 to Dr. Teri Rowles. Special thanks go to Scott Landry for providing scarring photographs of CCSN 02–225Mn and NEAq Eg 1238. Other necropsies were conducted by the Cape Cod Stranding Network, Atlantic Veterinary College, and New England Aquarium.

LITERATURE CITED

BARCO, S. G., W. A. MCLELLAN, J. M. ALLEN, R. A. ASMUTIS-SILVIA, R. MALLON-DAY, E. M. MEAGHER, D. A. PABST, J. ROBBINS, R. E. SETON, W. M. SWINGLE, M. T. WEINRICH AND P. J. CLAPHAM. 2002. Population identity of humpback whales (*Megaptera novaeangliae*) in the waters of the US mid-Atlantic states. Journal of Cetacean Research and Management 4:135–141.

CASWELL, H., M. FUJIWARA AND S. BRAULT. 1999. Declining survival probability threatens the North Atlantic right whale. Proceedings of the National Academy of Science 96:3308–3313.

FUNG, Y. C. 1981. Biomechanics. Springer-Verlag, New York, NY.

KNOWLTON, A. R., AND S. D. KRAUS. 2001. Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. Journal of Cetacean Research and Management Special Issue 2:193–208.

KNOWLTON, A. R., M. K. MARX, H. M. PETTIS, P. K. HAMILTON AND S. D. KRAUS. 2005. Analysis of scarring on North Atlantic right whales (*Eubalaena glacialis*): Monitoring rates of entanglement interaction: 1980–2002. National Marine Fisheries Service Final Report Contract # 43EANF030107. 19 pp.

KOZUCK, A., G. SALVADOR, J. KENNEY, J. ROBBINS, S. KRAUS, S. LANDRY AND P. CLAPHAM. 2003. Analysis of fishing gear involved in entanglements of right and humpback whales. Pages 1–8 *in* International Whaling Commission Sc/55/BC.

KRAUS, S. 1990. Rates and potential causes of mortality in North Atlantic right whales (*Eubalaena glacialis*). Marine Mammal Science 6:278–291.

MCKIRENAN, D., T. STOCKWELL, A. VALLIERE AND J. ODELL. 2002. Report of the Atlantic whale fishing gear advisory workshop. 6–8 May 2002, Narragansett, RI.

MOORE, M. J., A. R. KNOWLTON, S. D. KRAUS, W. A. MCLELLAN AND R. K. BONDE. 2005. Morphometry, gross morphology and available histopathology in North Atlantic right whale (*Eubalaena glacialis*) mortalities (1970 to 2002). Journal of Cetacean Research and Management 6:199–214.

NOWACEK, D. P., M. P. JOHNSON, P. L. TYACK, K. A. SHORTER, W. A. MCLELLAN AND D. A. PABST. 2001. Buoyant balaenids: The ups and downs of buoyancy in right whales. Proceedings of the Royal Society of London B 268:1811–1816.

ROBBINS, J., AND D. MATTILA. 2000. Gulf of Maine humpback whale entanglement scar monitoring results 1997–1999. National Marine Fisheries Service Final Report Order Number 40ENNF900253. 24 pp.

WILEY, D. N., T. D. PITCHFORD AND D. P. GANNON. 1995. Stranding and mortality of humpback whales, *Megaptera novaeangliae*, in the mid-Atlantic and southeast United States, 1985–1992. Fishery Bulletin 93:196–205.

Received: 24 November 2004
Accepted: 31 July 2005