MARINE MAMMAL SCIENCE, 24(2): 326–340 (April 2008)

DOI: 10.1111/j.1748-7692.2008.00184.x

Modeling whale entanglement injuries: An experimental study of tissue compliance, line tension, and draw-length

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

BECKY L. WOODWARD[1,2]
Mechanical Engineering Department,
University of Maine,
Orono, Maine 04469, U.S.A.
E-mail: woodward_becky@yahoo.com

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.

JOHN G. RILEY
School of Marine Sciences,
University of Maine,
Orono, Maine 04469, U.S.A.

ABSTRACT

Two test systems were developed to evaluate the influence of draw-length and tissue compliance on entanglement-induced epidermal abrasion in humpback (*Megaptera novaeangliae*) and right whale (*Eubalaena glacialis*) tissue samples. Under straight pull abrasion tests, an adult right whale fluke required 3.7 times the load and 15 times the draw-length of a right whale calf flipper to induce epidermal failure whereas a humpback fluke was intermediate between these extremes. A load applied

[1]Current address: Biology Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, U.S.A.

[2]Author to whom correspondence should be addressed.

tangentially to the leading edge of the fluke or flipper resulted in a substantial, but reversible, deflection of the leading edge in the direction of the applied load. The maximum possible deformation of the leading edge under shear load, prior to the line slipping relative to the skin, was defined as the tissue compliance limit. Oscillatory abrasion tests revealed that line draw-lengths exceeding the tissue compliance limit resulted in substantially increased tissue abrasion. In actual entanglements, line draw-length relative to the tissue compliance may determine if the line will cut into the body or simply press against the skin. Increasing the entangling line's ability to stretch in response to a load could potentially minimize sliding of the line relative to the skin and help mitigate entanglement injuries.

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

Entanglement in commercial fishing gear is one of the leading anthropogenic causes of serious injury and mortality in baleen whales (Knowlton and Kraus 2001, Robbins and Mattila 2004, Johnson *et al.* 2005). The North Atlantic right whale (*Eubalaena glacialis*) is of particular concern due to its critically low abundance (Kraus *et al.* 2005). Seventy-five percent of all photographed right whales show scarring indicative of rope and net cuts around the peduncle, and the rate of entanglement appears to be increasing (Knowlton and Kraus 2001, Knowlton *et al.* 2005). Additionally, approximately half (48%–57%) of North Atlantic humpback whales (*Megaptera novaeangliae*) bear similar signs of entanglement-related scarring about the peduncle, and approximately 8%–10% of the population receives new scars each year (Robbins and Mattila 2004).

In the western North Atlantic, right and humpback whales have been found entangled in all major types of fixed fishing gear (Johnson *et al.* 2005). Fishing gear modifications such as alternative line types, weak links, and acoustic deterrents have been suggested as possible means of reducing entanglement risks (Johnson *et al.* 2005, Kraus *et al.* 2005). However, the factors that govern entanglement injuries are not yet fully understood. Analysis of entangling lines and the resulting tissue damage to free swimming whales is extremely difficult to quantify, and entangling gear on stranded animals is often removed prior to forensic analysis, preventing in-depth evaluation during necropsy events (Moore *et al.* 2005).

Recently, Woodward *et al.* (2006) used a reciprocating load generator to model large whale entanglement injuries. The system loaded a line in an oscillatory manner, periodically causing it to go taut and then slack. This loading regime simulated an entanglement in which a fixed length of line anchored at two points on the body would be cyclically loaded and unloaded during swimming. Although the initial test system was effective in producing compression furrows similar to those observed on entangled whales, the abrading line did not cut through the epidermis. Between 1970 and 2002, in all cases in which right whale entanglement mortalities have been examined through necropsy, regions of epidermal penetration were noted (Moore *et al.* 2005).

An evaluation of the physical conditions leading to epidermal penetration will help inform recommendations for potential future gear modifications. Woodward *et al.* (2006) noted that a load applied tangentially to the leading edge of the fluke resulted in a substantial, but reversible, deflection of the leading edge and underlying tissues in the direction of the applied load. This pliant ability to deform in response

to the shear load generated by the pull of the line, yet readily return to its original state when unloaded, was defined as the tissue's compliance. This tissue compliance appeared to limit the abrasive impact of the test line by preventing it from sliding across the epidermal surface. It is hypothesized that the tissue compliance is essential to the abrasion resistance of whale skin.

To further examine this hypothesis, two new test systems were developed based upon the original design of Woodward *et al.* (2006) and used to compare right whale and humpback whale skin samples under controlled conditions. The role of tissue compliance in mitigating abrasive injuries was examined by (1) removing the compliance of the tissue and determining the shear load (mass applied to the test system to tension the abrading line) and draw-length (linear distance of travel of the abrading line) combination necessary to penetrate the epidermis; (2) determining the compliance limit, or maximum deformation of skin tissue under shear load prior to the line sliding relative to the skin; and (3) characterizing the effect of tissue compliance on abrasive damage generated by an oscillatory sawing motion using line draw-lengths below and above the compliance limit of the tissue.

METHODS

The following whale skin specimens were opportunistically collected at necropsy: (1) samples from the leading edge of a flipper for a right whale calf (Eg NEFL 0602, estimated 6.1-m [flukes missing from carcass] male, collected 22 January 2006 off Jacksonville Beach, FL), (2) samples from the leading edge of an adult right whale fluke (NEAq Eg 1004, 16-m female, collected 11 February 2004 at Nags Head, NC), and (3) the entire leading edge of a subadult humpback whale fluke (VAQS 2006 1007 Mn, 9.98-m female, collected 18 March 2006 at Virginia Beach, VA). Both flippers and flukes are known sites of entanglement injuries in large whales (Robbins and Mattila 2004, Johnson *et al.* 2005, Moore *et al.* 2005, Woodward *et al.* 2006). Carcasses from which samples were collected were listed as Code 3: Fair—moderately decomposed, but with internal organs basically intact (Geraci and Lounsbury 2005). Although the carcasses showed signs of cracked and sloughing skin in areas of high exposure, samples were only collected from regions where the epidermis remained firmly attached to the underlying tissue, generally those portions of the body that remained submerged and essentially refrigerated by the surrounding water as the carcass floated at sea.

Samples were wrapped in plastic, transported on ice to a storage facility (a process of several days), and stored in a −20°C freezer until testing was possible. Although the use of fresh tissue would be optimal, the logistical difficulties surrounding large whale necropsies precluded testing in the field and it was necessary to freeze the samples for storage until abrasive testing was possible. In addition to its original freezing, the fluke sample from Eg1004 was thawed during the prior Woodward *et al.* (2006) study and refrozen following a 4-d period of refrigeration and testing. For the current study, samples were thawed for 24 h in seawater prior to testing.

Two test systems were developed to examine fishing line-related entanglement injuries in large whales. These systems were designed to independently evaluate straight pull abrasion and oscillatory abrasion in relation to tissue compliance. As in Woodward *et al*. (2006), individual test sites on the samples were separated by a minimum distance of 2 cm to isolate test sites and maintain the integrity of the tissue. The resulting tissue indentation and damage were assessed following each test. Line

furrow patterns were photographically documented, and tissue abrasion was compared in two ways: (1) the maximum depth of epidermal/dermal penetration (±0.02 mm) and (2) the length of epidermal removal (±1 mm). Penetration depth was measured using digital calipers whereas the length of epidermal removal was measured along the curve of the sample with a flexible ruler. The length measurement included the region of exposed dermis but excluded cracked epidermis on either end of the furrow. This cracking could have represented an additional length of epidermal failure but could not be objectively measured.

Straight Pull Abrasion (SPA) System

A straight pull abrasion system was designed to measure the depth of epidermal penetration following a unidirectional pull of line over a standard draw-length (Fig. 1). Tissue samples were submerged and clamped in a static seawater tank with the leading edge of the sample facing downward toward the bottom of the tank. An abrading line passed between the upright clamping supports and under the leading edge of the test specimen, inducing a shear load on the tissue. The line was tensioned by means of a tensioning pulley that could slide horizontally along a track in the test system frame. A set of dead weights provided a means of adjusting the position of the tensioning pulley and the resulting shear load induced by the abrading line. A load cell (Model LC101, Omegadyne Engineering, Inc., Stamford, CT, USA) placed between the tensioning pulley and the dead weights allowed constant evaluation of line tension during testing, and a rotating shaft counter mounted on the tensioning pulley measured the distance the line was pulled across the test sample (±1 cm). A $\frac{1}{4}$-hp gear motor (Model 6ML51, Dayton Electric Manufacturing Company, Lincolnshire, IL) connected to a sailing winch (Model 5CT, Lewmar, Hampshire, UK)

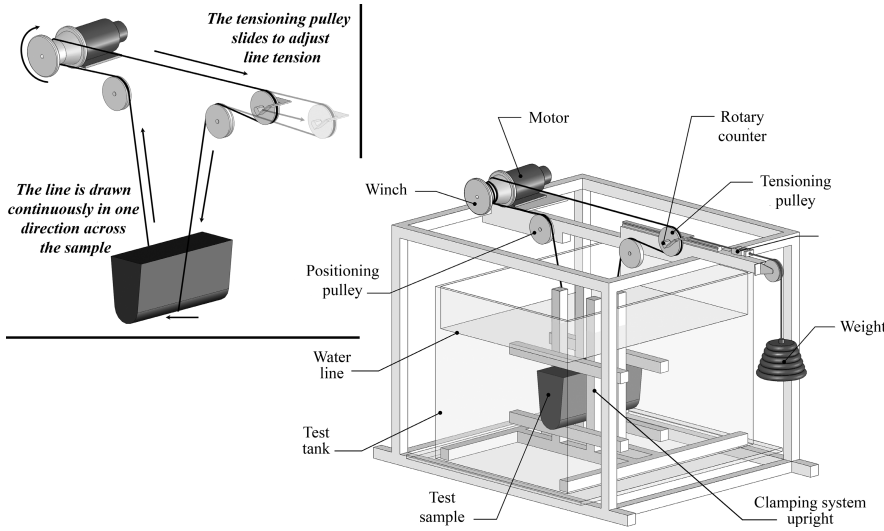

Figure 1. Straight pull abrasion (SPA) system. The SPA system provided a unidirectional pull on a continuous loop of line applying a shear load to the leading edge of the sample. The applied load was adjusted by means of the hanging weights and the tensioning pulley that could slide along a track in the frame support.

pulled a spliced loop of line unidirectionally across the test sample inducing a shear load on the tissue.

The clamping system uprights supporting the test specimen were spaced 7.6 cm apart to minimize flexure of the sample in response to the applied shear load. To ensure accurate pull distances across the sample regardless of tissue compliance, tension was first applied to the abrading line by adding weight to the tensioning pulley. The sailing winch was then turned manually until the compliance of the tissue was reached and the abrading line began to slide with respect to the epidermis. At this point, the rotary counter was zeroed. A standard 3.1-m draw-length of line was then pulled across the fluke sample at a continuous rate of 5 cm/s. 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 positioning of the tensioning pulley. Ideally tests would have been conducted at different draw-rates; however, the limited number of available tissue samples precluded such rate dependent testing. All tests in this study were conducted at a single fixed draw-rate.

The line samples used were all of three-stranded, twisted construction. Both new and used polypropylene float and polypropylene/polyester blend sink lines were tested. Float line diameters of 6.4 mm and 9.5 mm as well as a sink line diameter of 9.5 mm were included. The used rope samples were cut from the same line used by Woodward *et al.* (2006). These lines were previously used for lobstering (Southwest Lobster and Fish Unlimited, Southwest Harbor, ME, USA) and contained ingrained sediments and fraying rope fibers. To create a continuous loop of line, a 3.5-m section was cut and the ends joined using a 15-cm splice. Two sets of tests were conducted with the SPA system.

(1) *Point of epidermal penetration for each test specimen*—A standard draw-length of 3.1 m was used with new 9.5-mm diameter float line to determine the load and draw-length combination necessary to penetrate the epidermis for each of the tissue specimens. Load on the system was increased in 2.3-kg increments from 2.3 kg to 31.8 kg. Epidermal failure was defined as substantial cracking of the epidermis and exposure of the underlying dermis. If epidermal failure did not occur at a given load with the 3.1-m draw-length, the line was moved to a new test location and run with an additional load. If the 31.8-kg load and the 3.1-m draw-length failed to penetrate through the epidermis to the dermal layer, the draw-length was increased in 3.1-m increments until failure was achieved using the 31.8-kg load. In all cases, the line was moved to a new location between tests.

(2) *Influence of line type and line diameter*—Three tests were conducted for each of the four different 9.5-mm diameter line types (new and used float and sink) to determine if there was a difference in tissue abrasion when using different types of abrading line. Tests were conducted in random order on samples from the humpback fluke using a standard 3.1-m draw-length with a 31.8-kg load. Depth of penetration and length of epidermal removal were measured. The results were compared using a pairwise Bonferroni-corrected Wilcox-Mann-Whitney test at the $\alpha = 0.05$ level.

Similarly the effect of rope diameter on skin abrasion was also examined. Abrasion tests using 6.4-mm and 9.5-mm diameter new float lines were conducted on the leading edge of the humpback fluke specimen using a 31.8-kg load and a 3.1-m draw-length. Each line diameter was tested twice for a total of four tests between the two line diameters, moving to a new test site between test runs. Again depth of penetration and length of the epidermal removal were recorded.

Oscillatory Pull Abrasion System

An oscillatory pull abrasion (OPA) system was designed to measure the tissue compliance limit in a test sample under a shear load and then to experimentally model abrasion resulting from a given back and forth oscillatory shear load with line draw-lengths below or above this tissue compliance limit (Fig. 2). The OPA system used a series of upper and lower positioning pulleys to position an abrading line across the leading edge of the test sample. The upper right pulley served as a tensioning pulley that could slide along a horizontal track in the system frame support. Tension in the abrading line was maintained using an adjustable weight connected to the tensioning pulley.

The rotary motion of a $\frac{1}{4}$-hp motor was converted into linear motion through a slider-crank mechanism that drove a sleigh attached to the line between the upper positioning pulley and tensioning pulley. The sleigh's motion in turn drove the back and forth sawing motion of the abrading line across the leading edge of the test sample. The draw-length of the abrading line could be adjusted by changing the length of the arm on the slider-crank mechanism. A position transducer (Model PT101, Celesco Transducer Products, Inc., Chatsworth, CA, USA) was used to measure the precise distance of linear travel in the line, whereas two load cells (Model LC101, Omegadyne Engineering Inc., Stamford, CT, USA and Model MLP100, Transducer Techniques, Inc., Temecula, CA, USA) were inserted in either side of the line system to simultaneously measure load on both sides of the tissue sample.

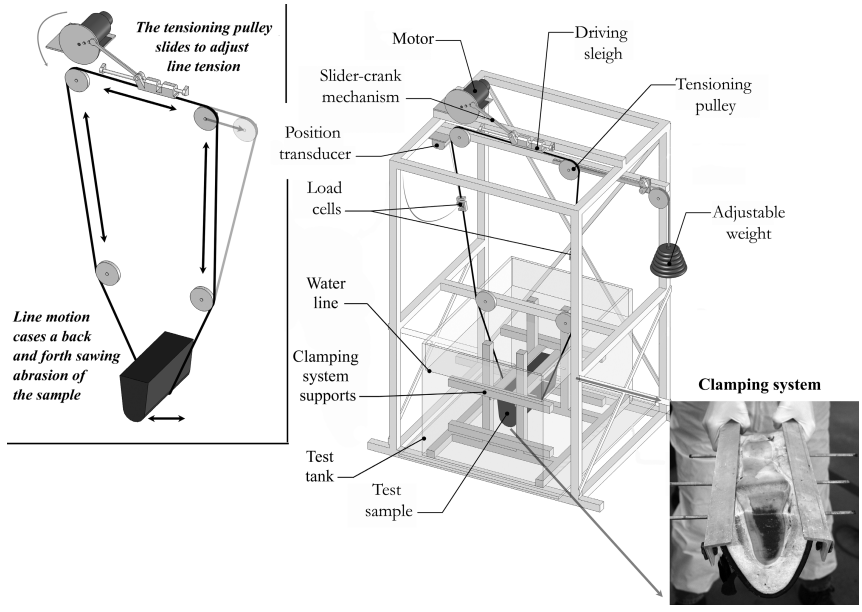

Figure 2. Oscillatory pull abrasion (OPA) system. The base of the sample was clamped (lower inset) leaving the leading edge of the sample free to flex in response to the pull of the abrading line (upper inset). In this way, tissue compliance in the sample could be measured and the abrasion due to line draw-lengths above and below the tissue compliance limit could be evaluated.

To simulate the natural compliance of the fluke and flipper samples as closely as possible, a new clamping technique was developed for use with the OPA system. In the SPA tests, the tissue sample was securely clamped with bars pressing along both the sides and upward against the leading edge of the sample, limiting sample flexure as much as possible. In the OPA tests, however, only the base of the sample was clamped leaving the leading edge free to flex without any form of restraint. Three 6.4-mm diameter threaded rods were inserted through the base of the sample and secured to two pieces of 90° angle irons (3.8-cm wide and 61-cm long). The ends of these angle irons were then securely bolted to the original clamping frame within the seawater tank (lower inset Fig. 2).

Two sets of tests were conducted with the OPA system using the humpback whale fluke and the right whale calf flipper specimens.

(1) *Tissue compliance limit*—The tissue compliance of each sample was determined using a 9.5-mm diameter new float line. A shear load was applied to the sample via the driving sleigh until the static friction between the abrading line and the skin was overcome and the line started to slide across the epidermal surface. The sleigh was driven at a rate of 5 cm/s. The linear distance of travel of the abrading line between its unloaded and loaded/starting-to-slide positions, which reflected the shearing deformation of the underlying tissues (Fig. 3), was measured to the nearest millimeter using the position transducer. The applied load was simultaneously recorded on a laptop computer using the load cells. The direction of the applied shear load was then reversed until static friction was overcome in the opposite direction, and the linear distance of travel of the abrading line was measured again. The measured distance of line traveled (*i.e.*, the shearing deformation of the underlying tissues)

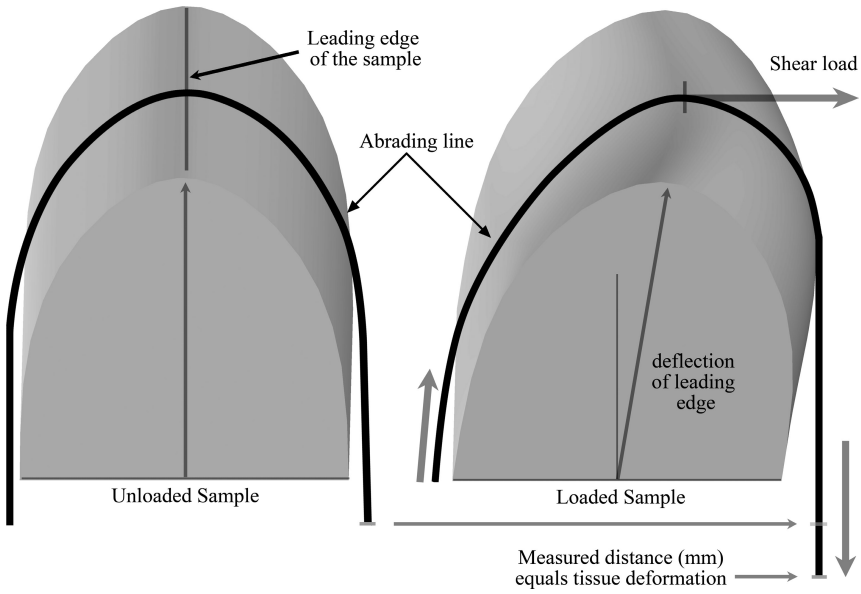

Figure 3. Tissue compliance in response to a shear load. As the sample was loaded, the leading edge deflected in the direction of the applied load. Linear displacement of the abrading line reflected the tissue deformation.

in both directions were added together and recorded as the tissue compliance limit (mm), or maximum possible deformation of skin tissue under shear load prior to the line slipping relative the skin. During compliance limit testing, tissue deformations were found to be reversible with no visible damage to the tissue. To conserve tissue samples for other abrasive test procedures, this nondestructive compliance limit test was repeated six times at a single site on each sample to determine the average tissue compliance limit for the sample.

(2) *Effect of tissue compliance on abrasion resistance during oscillatory sawing*—Two 2-h oscillatory tests were conducted on each sample using a 9.5-mm diameter new float line: one with a short 2.5-cm line draw-length and one with a longer 7.6-cm line draw-length. Each line draw-length was tested twice per tissue sample, using a new test site for each test run. The short 2.5-cm draw-length was selected to be just at or slightly below the tissue compliance limits of the right whale calf flipper and humpback whale fluke samples, whereas the longer 7.6-cm draw-length was selected to be well above their compliance limits. Test loads were selected to be 2.3 kg above the load needed to penetrate the epidermis with a 3.1-m pull in the SPA system (11.3 kg for right whale calf flipper and 31.8 kg for humpback whale fluke). Depth of penetration and length of the epidermal removal were recorded.

RESULTS

Straight Pull Abrasion (SPA) Testing

Despite differences in leading edge epidermal thicknesses (8.0 mm, 5.1 mm, and 4.9 mm for the right whale calf flipper, adult right whale fluke, and humpback whale fluke, respectively), the mode of epidermal failure was similar in each of the tissue samples (Fig. 4). Prior to abrasion tests the epidermal surface was typically smooth with a slick rubber-like exterior. This superficial stratum externum layer of epidermis (St. Aubin *et al*. 1990) was removed during an initial period of abrasion, revealing the deeper stratum intermedium layer underneath, where the exposed tips of the dermal papillae gave the tissue a rougher sponge-like appearance. As abrasion continued, cracking of the intermedium layer began. Initially, crack formation occurred directly beneath and in the same direction as the motion of the abrading line. Subsequently, the shear forces began to tear the stratum intermedium between the dermal papillae. Cracking of the epidermis extended through its full thickness with finger-like projections of dermal papillae and overlaying epidermis remaining firmly attached to the dermis beneath, but separated from adjacent papillae pillars (Fig. 4b, 5). Cracks appeared at approximately 45° to the direction of line travel and created a rug-like patchwork of papillae and epidermal projections. With continued abrasion, this cracking of the epidermis intensified and was followed by the epidermis pulling out in discrete pieces, separating from the underlying dermis at the dermal/epidermal interface (Fig. 4b, 5).

A substantial difference in epidermal abrasion resistance was found between the three test specimens. For the calf flipper, a 3.1-m draw-length with a 6.8-kg load produced epidermal cracking, whereas an 11.3-kg load produced a region of epidermal removal 15.76 mm long with a maximum depth of 8.44 mm. Thus, the test load required for epidermal penetration occurs somewhere between 6.8 and 11.3 kg using a 3.1-m draw-length. Using the same 3.1-m draw-length, the humpback whale fluke withstood a 27.7-kg test load prior to epidermal penetration. The right whale fluke

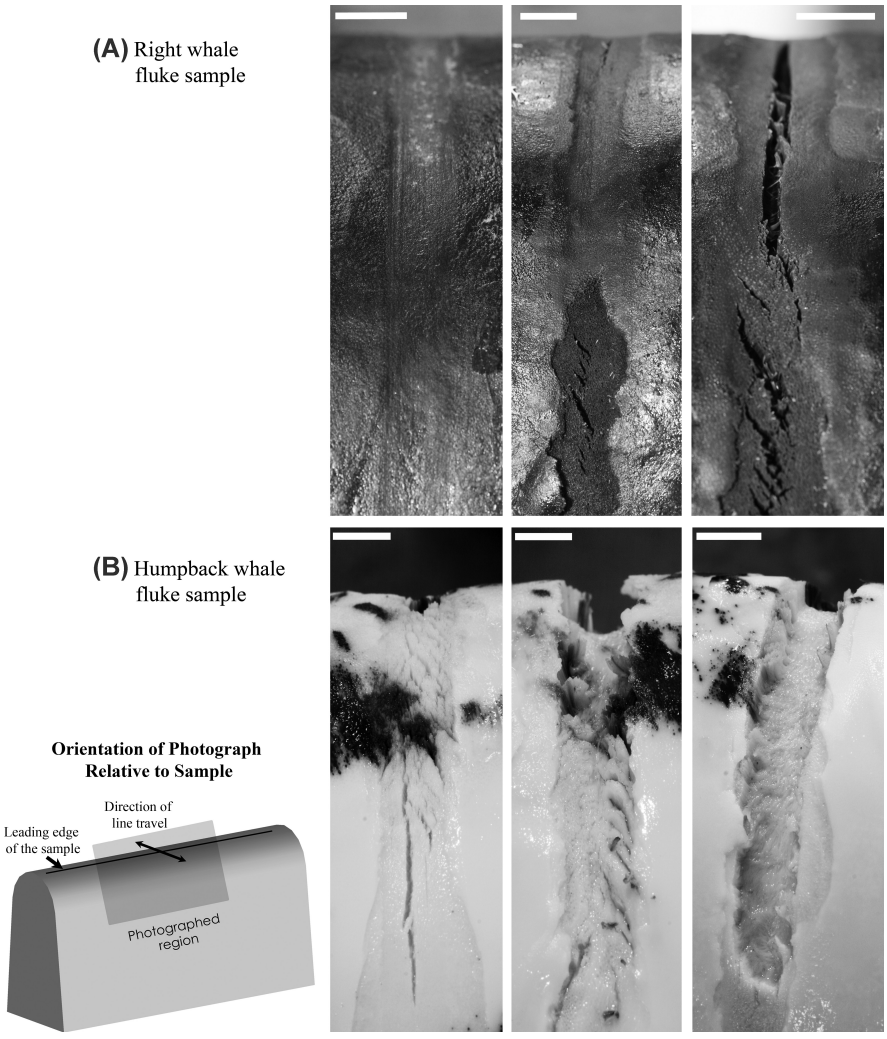

Figure 4. Progressive stages of epidermal failure: (**A**) early stages in adult right whale fluke, (**B**) later stages in humpback whale fluke. Sequence progresses from left to right. Scale bars represent 1 cm. When photographed, samples were oriented with the leading edge facing upward (left inset). Abrading line motion was back and forth into and out of the paper.

specimen showed an even greater resistance to abrasion. A 31.8-kg load and a 45.7-m draw-length produced only the initial stage of epidermal cracking beneath the abrading line.

Line diameter appears to influence tissue abrasion more than line type. No statistical difference in maximum furrow depth or length of epidermal removal was noted between 9.5-mm diameter new or used float and sink lines ($P \geq 0.4$). Limited availability of tissue samples prevented a statistical analysis of line diameter effects on abrasion. However, preliminary tests comparing 6.4-mm and 9.5-mm diameter new float lines revealed that the smaller diameter line cut consistently deeper into

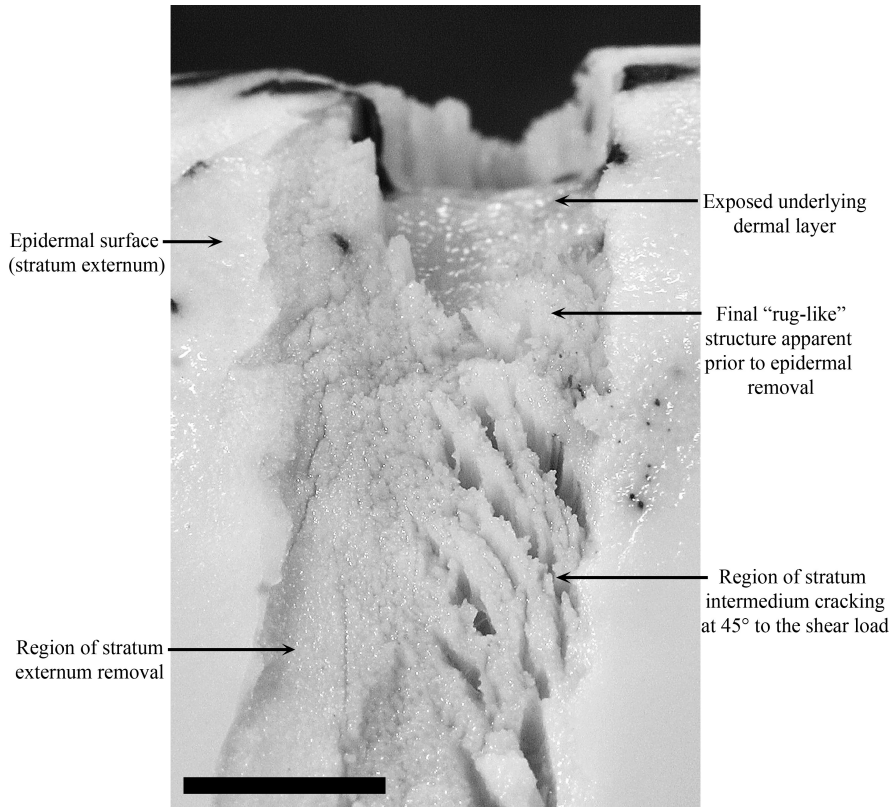

Figure 5. Closeup image of the progressive stages of epidermal failure in humpback whale fluke. Scale bar represents 1 cm.

the humpback fluke tissue and had a greater length of epidermal removal for a given load and draw-length combination (Table 1). The smaller diameter line concentrated on the applied shear load over a smaller contact area, increasing the shear stress, or force/unit area exerted by the line on the tissue, and intensifying the abrasive effect.

Oscillatory Pull Abrasion (OPA) Testing

Using a 9.5-mm new float line and a 11.3-kg load on the test system, the average compliance limit in the right whale calf flipper was determined to be 2.4 cm with a standard deviation about the mean (SD) of ± 0.08 cm. The average compliance limit in the humpback whale fluke was determined to be 4.45 ± 0.10 cm using a 71.8-kg load on the test system.

A marked difference in tissue abrasion resulted from oscillatory tests conducted with line draw-lengths near or below the compliance limit *vs.* those above the tissue compliance limit (Fig. 6). For both the right whale calf flipper and the humpback whale fluke, the longer 7.6-cm draw-length cut deeply into the underlying dermis whereas the 2.5-cm draw-length did not crack the epidermis. In the calf flipper, the 7.6-cm draw-length test resulted in a maximum furrow depth 5.9 times deeper than

Table 1. Comparison of tissue abrasion and line diameter. Abrasion tests were conducted on the humpback whale fluke using a 31.8-kg load on the SPA test system with a 3.1-m draw-length. Measurements provided in mm (mean ± SD).

Line diameter	Maximum furrow depth	Length of epidermal removal
6.4	6.9 ± 0.5	132.0 ± 21.2
9.5	4.8 ± 1.2	52.5 ± 12.0

that of the 2.5-cm draw-length (22.15 mm compared to 3.78 mm). The 7.6-cm draw length also left a 139-mm long region of exposed dermis whereas the 2.5-cm draw-length only left a shallow furrow that did not penetrate through the entire depth of the epidermis or even show cracking around the dermal papillae. The difference in furrow depth was even greater in the humpback whale fluke. The 7.6-cm draw-length caused a maximum furrow depth 8.5 times deeper than the 2.5-cm draw-length (33.1 mm compared to 3.9 mm) and left a 169-mm length of dermal tissue exposed.

The characteristics of the abrasion furrow also differed between the 2.5-cm and 7.6-cm draw-lengths in each specimen. The shorter 2.5-cm draw-length produced a shallow furrow with extensive streaking and a three-stranded dimpled pattern representative of the three-stranded rope construction as noted in the Woodward *et al.*

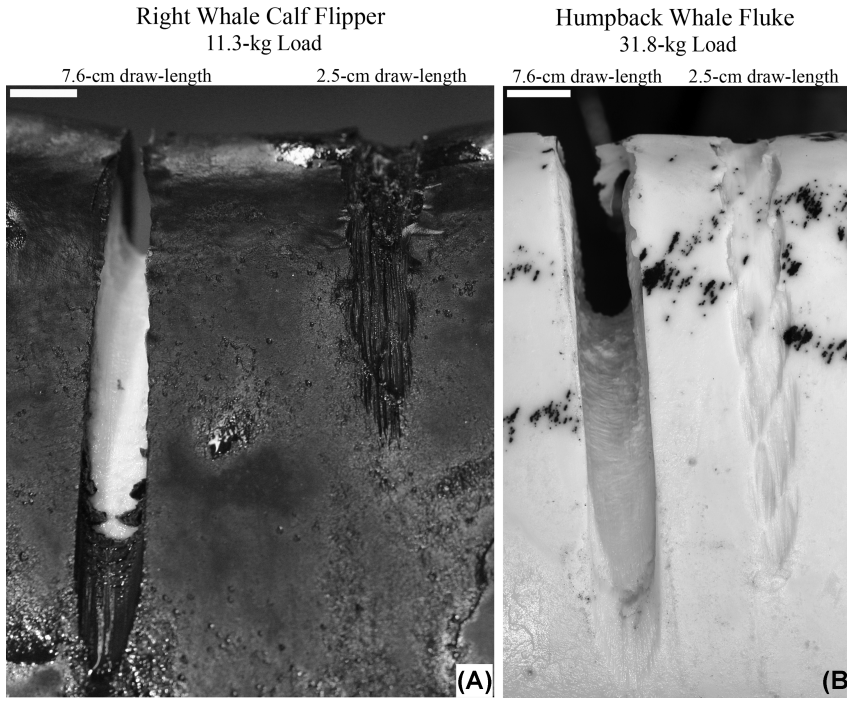

Figure 6. Comparison of oscillatory abrasion furrows using different draw-lengths: (**A**) right whale calf flipper, (**B**) humpback fluke. The 7.6-cm draw-length cut substantially deeper into the skin tissue for both tissue specimens. Scale bar represents 1 cm.

(2006) study. The longer 7.6-cm draw-length caused a rapid progression through the stages of epidermal failure, leaving a smooth furrow where the epidermis and dermal papillae were completely removed. No dimpling or cracking of the exposed dermal tissue was evident.

DISCUSSION

With regard to oscillatory loading, tissue compliance limit appears to be a primary factor in mitigating the abrasive impact of rope on whale skin. Tests revealed that a draw-length above the tissue compliance limit cut deeply into the dermal tissue whereas draw-lengths just at or below the compliance limit did not penetrate completely through the epidermis in either the right whale calf flipper or the humpback whale fluke (Fig. 6). These results suggest that although characteristic indention furrows such as those found in the Woodward *et al.* (2006) study are produced when lines are pressed into the skin in an oscillatory manner, larger scale epidermal tissue removal likely does not occur until static friction is overcome and the line slides across the epidermal surface.

In this study, the stages of epidermal failure appeared consistent across specimens. The presence of solid keratinized epidermal rods extending upward from the tips of the dermal papillae through the epidermis to its exterior has been suggested to provide support to regions of thick epidermis in bowhead whale skin (Haldiman *et al.* 1981, 1985). Similar keratinocyte rosettes have been documented in right whale calf epidermis (Reeb *et al.* 2005). The failure mode of the samples in this study suggests that the dermal papillae with their keratinized superstructures may have a greater resistance to a shear load than the intermedium epidermal cells in between them.

Although the failure mechanism was similar, the ability of the skin to resist abrasion, measured as both the maximum depth of penetration and the length of epidermal removal, differed between samples. For example, the right whale calf flipper had the thickest epidermis, but in straight pull abrasion tests, required the lowest load (8.6 kg) and draw-length (3.1 m) combination to penetrate the epidermis. The humpback and right whale fluke specimens had similar skin thicknesses, but required different loads (27.7 kg *vs.* 31.7 kg, respectively) with dramatically different draw-lengths (3.1 m *vs.* 45.7 m, respectively) to generate epidermal failure. The right whale fluke withstood 15 times the draw-length (3.1 m *vs.* 45.7 m) with 3.7 times the load (8.6 kg *vs.* 31.7 kg) of the calf flipper. Potential factors that may have influenced the difference in the abrasion resistance among the three specimens include the age of the animal from which tissue samples were collected, species-specific variations in mechanical properties of the epidermis, differences in dermal structure between body regions (flippers *vs.* flukes), and any freeze/thaw effects on the tissue.

Due to the necessity of opportunistic sample collection, consistency in age, sex, species, and body region could not be maintained across test specimens. Whales from which the samples were collected ranged from a 1–2-mo-old male right whale calf to a 3-yr-old subadult female humpback to a mature 24-yr-old adult female right whale.[3, 4] The tensile properties of skin in other vertebrates are known to change with

[3]North Atlantic Right Whale Consortium Necropsy Data Base, New England Aquarium, Boston, MA, 15 January 2006.

[4]Personal communication from Susan Barco, Stranding Response Coordinator for the Virginia Aquarium, Virginia Beach, VA, 11 April 2006.

age, typically increasing in strength and decreasing in elasticity through middle age (Cua *et al.* 1990, Vogel 1994, Cloete *et al.* 2004). It is unknown whether similar age effects may affect skin properties and abrasion resistance in cetaceans. It was qualitatively observed during testing that the amount of oil exuded from the tissue samples was noticeably different among the specimens and may also have contributed to differences in abrasion resistance. Older whales tend to have oilier tissues and the interior surfaces of the adult right whale specimen, exposed when the sample was sectioned from leading edge of the fluke, were coated in a layer of congealed oil not encountered in either the humpback fluke or the right whale calf flipper. The oil content of this specimen may have influenced the coefficient of friction between the epidermal surface and the abrading line, helping to minimize abrasive injuries.

Without access to homologous aged samples, it is uncertain whether or not the differences in epidermal abrasion resistance observed represent skin property differences related to body regions (flukes *vs.* flippers) or are the result of the age of the animal. Knowlton *et al.* (2005) noted that a higher percentage of new entanglement scars are observed on juvenile animals. Assuming the difference in abrasion resistance is due to age alone, it may be that non-abrading entanglements (*e.g.*, noninjury producing and self disentangled) occur in adults more often than has been previously reported based on scarring studies. However, if the difference in abrasion resistance noted between flippers and flukes in this study is due to mechanical differences in skin structures between the two body regions rather than age, it may be that flippers could be more susceptible to abrasive injuries than flukes. Future studies examining the relative differences between flippers and flukes from the same animal would help determine if the site-specific differences in abrasion resistance noted in this study are related to age or regional differences in epidermal/dermal mechanical properties.

Variations in the condition of the sample may also play an important role in abrasion resistance. Optimally tests would be conducted on fresh samples that have never been frozen. Unfortunately, samples could only be collected from stranded carcasses and the degree of sample freshness varied due to the length of elapsed time between death and the carcass washing ashore. All samples were collected from carcasses that were listed as Code 3 on the necropsy reports (Geraci and Lounsbury 2005). Carcasses were considered to be in fair condition with a moderate degree of decomposition, and tissue samples were only collected from regions where the epidermis remained firmly attached to the underlying tissue. However, with the decomposition of the carcass, some of the tissue strength is lost due to postmortem autolysis. Freeze/thaw effects may also have added to the tissue degradation. Out of necessity, samples were frozen until the abrasion testing could be performed. The influence of the freeze/thaw process on whale skin has not been examined. However, a number of studies have been undertaken on a variety of tissues from different mammalian species. Studies on the tensile properties of muscles in dogs suggest that the freeze/thaw process significantly reduced the tensile strength of the tissue (Gottsauner *et al.* 1995). On the other hand, studies on human skin reported an increased variability about the mean but no change in the average tensile strength of the skin after freezing (Millington and Wilkinson 1983). Similar results were reported for freeze effects on the ligaments of rabbits (Woo *et al.* 1986). It is unclear whether the freeze/thaw process may weaken the extracellular matrix structure of whale skin, but it is reasonable to presume that fresh and unfrozen tissue would be stronger than frozen/thawed tissues taken from a carcass in fair condition. Thus, the results presented here provide a conservative representation of the tested tissue's resistance to rope abrasion.

Despite the limitations imposed by the small number of samples available for testing, this study shows that preventing line movement across the surface of the epidermis is a critical factor in mitigating the abrasive impact of rope on whale skin. In actual entanglement situations, draw-length may be the critical component that determines if the line will cut into the body or simply press against the skin. Decreasing line draw-lengths below the tissue compliance limit could mean the difference between a less harmful furrow in the epidermis and a deep laceration. For a line anchored at both ends, a stretchy rope that could lengthen as the whale's body flexed, could potentially reduce the draw-length of the line across the skin. A line's modulus (N/m^2) provides a measure of its stretchiness and ability to resist elongation under a given tensile load. It is determined by the ratio of stress (force/unit area) applied to the line and the resulting strain (change in length/original length) of the line. A low modulus line has a greater capacity to stretch in response to a load than a high modulus line. As such, decreasing the line modulus for fishing gear could potentially lead to a reduction in serious large whale entanglement injuries.

Fishing with a low modulus line has both positive and negative features. In the event of a broken line, the risk of recoil is substantially increased with a stretchy rope. On the other hand, if the low modulus line hung on a bottom obstruction, the increased stretch of the line may result in a less catastrophic line/hauler interaction. Further tests are required to examine both the abrasive effects of a low modulus line on whale skin and to investigate the impact of such a line modification on the fishing performance of the gear.

Acknowledgments

This research was supported by a grant through the National Fish and Wildlife Foundation. The authors would like to thank the necropsy team members for obtaining samples from NEAq Eg 1004, Eg NEFL 0602, and VAQS 2006 1007 Mn. Necropsy team members included individuals from the Virginia Aquarium, UNC Wilmington, and Woods Hole Oceanographic Institution. In particular, thanks go to Sue Barco, Bill McLellan, and Charley Potter for their aid in the acquisition of tissue specimens. Thanks also go to Dr. Ann Pabst for her helpful suggestions on the manuscript. Samples were obtained under NMFS permit number 932-1489-03/PRT009526 issued to Dr. Teri Rowles and the protocol approved by WHOI Institutional Animal Care and Use Committee.

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Received: 27 October 2006
Accepted: 5 November 2007