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Rope trauma, sedation, disentanglement, and monitoring-tag associated lesions in a terminally entangled North Atlantic right whale (*Eubalaena glacialis*)

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ABSTRACT

A chronically entangled North Atlantic right whale, with consequent emaciation was sedated, disentangled to the extent possible, administered antibiotics, and satellite tag tracked for six subsequent days. It was found dead 11 d after the tag ceased transmission. Chronic constrictive deep rope lacerations and emaciation were found to be the proximate cause of death, which may have ultimately involved shark predation. A broadhead cutter and a spring-loaded knife used for disentanglement were found to induce moderate wounds to the skin and blubber. The telemetry tag, with two barbed shafts partially penetrating the blubber was

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shed, leaving barbs embedded with localized histological reaction. One of four darts administered shed the barrel, but the needle was found postmortem in the whale with an 80° bend at the blubber-muscle interface. This bend occurred due to epaxial muscle movement relative to the overlying blubber, with resultant necrosis and cavitation of underlying muscle. This suggests that rigid, implanted devices that span the cetacean blubber muscle interface, where the muscle moves relative to the blubber, could have secondary health impacts. Thus we encourage efforts to develop new tag telemetry systems that do not penetrate the subdermal sheath, but still remain attached for many months.

Key words: right whale, *Eubalaena glacialis*, entanglement, trauma, shark predation, tag.

Entanglement in fishing gear is a major cause of morbidity and mortality in large whales (Knowlton and Kraus 2001, Cassoff *et al.* 2011). In the North Atlantic right whale (*Eubalaena glacialis*) these events have been shown to result in outcomes that range from transient to persistent entanglements. Persistent cases can resolve spontaneously or after human intervention, they can become very long term (years), or result in death after about 6 mo (Moore *et al.* 2006). Examination of entanglement mortalities has shown a variety of chronic impacts for persistent terminal entanglements (Moore *et al.* 2004). Thus there remains an urgent need for better entanglement avoidance and individual entanglement mitigation. Recent measures to reduce the impact of entanglement in the United States have included requirements for weak links on buoy lines and sinking ground lines between fishing traps and pots (U.S. Federal Register 2007), but lethal entanglements continue to occur (Pettis 2010). Disentanglement continues to be one option until effective preventative measures are developed, but many efforts are unsuccessful and there is no means of controlling the time between an entanglement and its first discovery by responders. Most disentanglement of free-swimming whales carrying fishing gear has depended on the addition of buoys, drogues, and boats to limit the animal to the surface, tire it, and enhance gear removal with cutting tools. Avoidance of an approaching boat, that is attempting disentanglement, is a common problem recently addressed by use of chemical sedation (Moore *et al.* 2010). Protocols using intramuscular drugs, delivered by ballistic syringe and 30 cm long stainless steel needle, are not benign, and require monitoring of sedation, any affixed equipment, animal condition, and survival. Tagging of animals which have been subject to disentanglement attempts is one monitoring method.

Implantable telemetry tags for long term monitoring of large whales are usually of a length sufficient to penetrate into the axial muscle (Mate *et al.* 2007). Use of this tag type to monitor post-disentanglement survival in clinically compromised animals would be very valuable. But concerns include, their invasive nature, and reports of both localized and regional swellings associated with their use (Mate *et al.* 2007). Less invasive attachment can be achieved with a tag that does not penetrate the subdermal sheath and into the axial muscle. Such tags have recently been used in the dorsal fins of numerous odontocetes (Andrews *et al.* 2008, Schorr *et al.* 2009), but rarely in baleen whales, given concerns of relatively short lived attachment without penetration below the subdermal connective tissue sheath (Mate *et al*. 2007).

This paper examines the impacts of a range of human interactions on a chronic, severe whale entanglement, including: (1) chronic rope trauma, (2) invasive disentanglement devices, (3) a dermally mounted telemetry tag, and (4) a remote drug delivery system. It also serves as a document of initial techniques in this challenging approach to resolve large whale entanglement.

Methods

A juvenile female North Atlantic right whale, (*Eubalaena glacialis*), was first sighted entangled on 25 December 2010, although body condition at that time suggested it had already been entangled for several months.[2] The whale was identified at necropsy as Field No. EgNEFL1103, cataloged post mortem as New England Aquarium Catalog No. Eg 3911, a 2009 calf of Catalog No. Eg 2611, in its first year after weaning. The whale had a complex entanglement with rope entering its mouth at a minimum of six sites, and wrapping both flippers, with approximately 30 m of this rope trailing aft of its flukes (Fig. 1). In total, approximately 132 m of 12 mm diameter floating synthetic twisted rope was removed; the rope appeared to be the same type/manufacture throughout. The rope included at least six gangions (connecting lines used to attach to fishing traps) of various diameters/lengths comprised of twisted and braided synthetic line. The distance between gangions averaged approximately 22 m (range = 20–24 m). Fragments of vinyl coated trap mesh remained attached to two gangions.

Despite partially successful initial disentanglement efforts without sedation, including shooting a cruciform broadhead cutter 10.2 cm in width, (Fig. 2a;

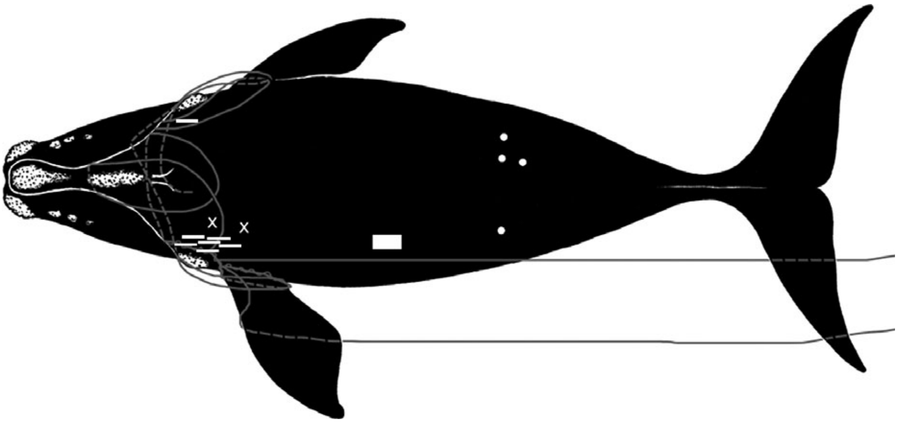


Figure 1. Schematic diagram of the entanglement of #3911 at first sighting (rope in gray, dashed lines connote rope inside or under the whale), including known lesion sites for: sedation and antibiotic whale darts (white dots), LIMPET tag (white rectangle), spring-loaded knife (white horizontal lines), and broadhead cutter (white X's).

[2]Personal communication from Heather Pettis, New England Aquarium, Central Wharf, Boston, MA 02110, 1 May 2011.

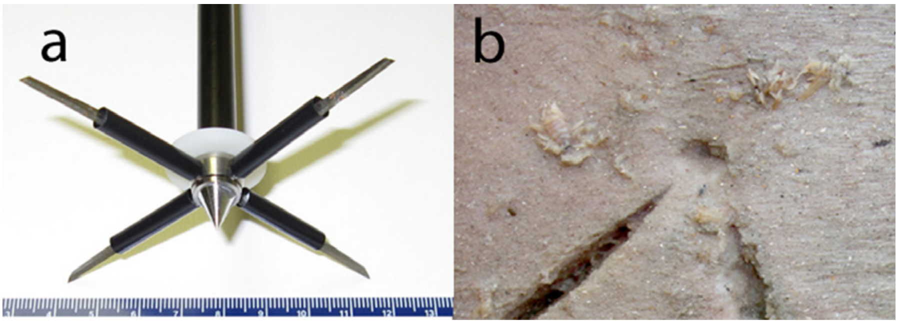
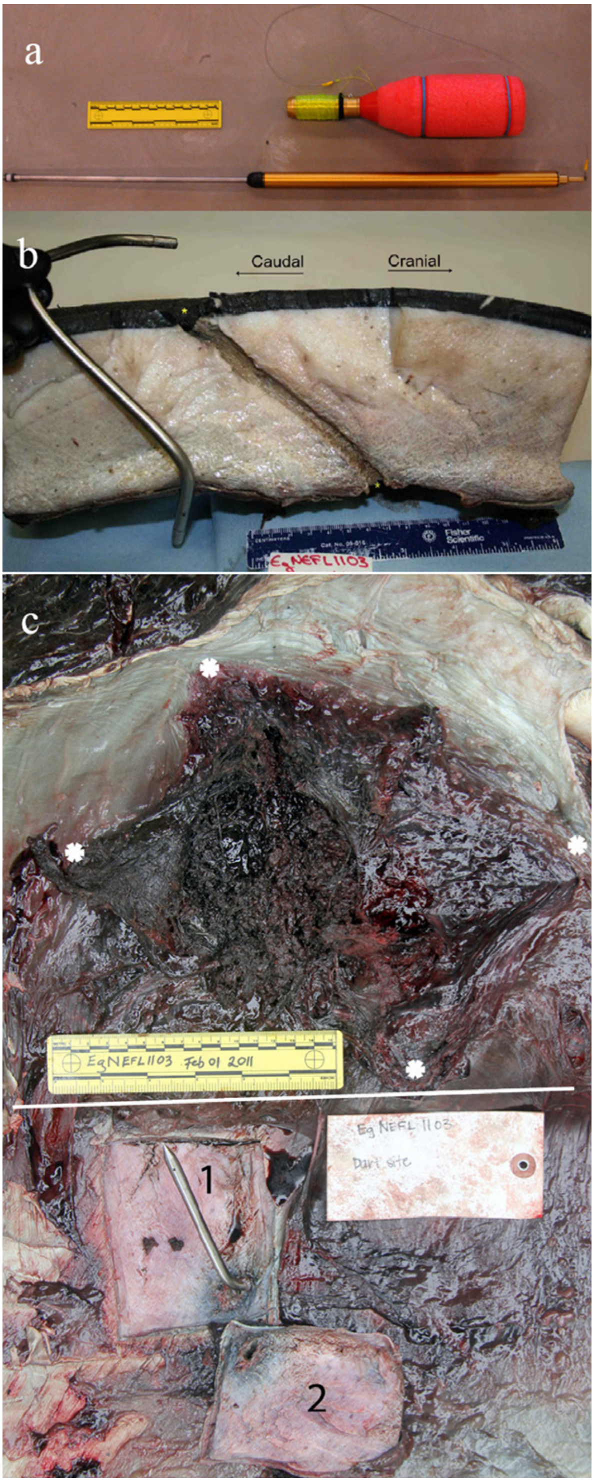


Figure 2. (a) Cutting head of a broadhead cutter. The blades are sheathed for aerodynamic flight. Upon impact, the sheaths are sliced by the blades and dispersed. (b) Broadhead cutter lesion in right whale #3911.

125 grain Guillotine, part number ASG125, Arrowdynamic Solutions, http://www.arrowds.com), with a low-powered crossbow on 29 December 2010, to attempt to cut entangling lines, the animal remained seriously entangled.

On 15 January 2011 additional disentanglement efforts were conducted following sedation. After attachment of a suction cup mounted Dtag (Johnson and Tyack 2003), between 1024 and 1354 local time, four 56 mL intramuscular darts (Fig. 3a) were deployed. These consisted of a 30 cm long, 7 mm outside diameter, 0.9 mm wall thickness, stainless steel needle, with a carbon fiber liner, a solid tip, and three side injection ports. The syringe barrel had a 2 cm outside diameter and was 33 cm long, as described previously (Moore *et al*. 2010), but modified with a 24 kg test 20 m long monofilament tether to a conically nosed foam float (7 cm diameter, 19 cm length, with a 2 cm diameter aluminum tubular shaft). Body weight was estimated at 7,000 kg, by comparing aerial image body length to width ratios to "normal" right whales (Miller *et al.* 2012) and weights at age (Moore *et al*. 2004). The darts were deployed as follows: one for sedation (28 mL total volume: 14 mL each of 50 mg/mL butorphanol and midazolam. *i.e.*, 0.1 mg/kg body weight of each, at local time 1023), one for sedation reversal (56 mL: Naloxone 50 mg/mL 0.05 mg/kg 7mL Flumazenil 0.1 mg/mL 49 ml at local time 1143), both in the right flank, and two (56 mL) for antibiotic administration, one in the right flank (1242) and one in the left (1353). A typical injection site has been previously illustrated (Figure 4 in Moore *et al*. 2010, where an injection dart is visible on the right flank of the animal, seen as a yellow metallic cylinder). A total of 17.6 g of antibiotic Ceftiofur (220 mg/mL, Pfizer Inc, Madison, NJ) was given. On recovery of the reversal dart it was discovered that a faulty pressure valve resulted in no reversal dose being delivered. The second antibiotic dart in the left flank contained 24 mL of drug, made up to 56 mL with sterile water. All the darts were in the epaxial muscle overlying the kidney region.

After sedation, aversion to boat approaches was markedly reduced and two spring-loaded knives were used to cut embedded ropes exiting both sides of the mouth (Fig. 4a). The tools had 10 or 15.25 cm wide blades with a maximum mechanical throw of 6 cm, and were mounted on a handheld carbon fiber pole. The throw is activated when a plunger contacts the skin surface, releasing the knife spring. Two deployments to cut embedded line were made with the 10 cm blade on the left side of the head, but the knife spring did not discharge. Six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attempts were made on the left side of the head and one attempt was made on the right side of the head with the 15.25 cm blade and the knife activated in each case. A successful cut parting the lines trailing from the left side of the mouth was made on the sixth attempt that triggered on the left side.

After sedation and disentanglement (1114–1154), a sterilized Low Impact Minimally-Percutaneous External-electronics Transmitter (LIMPET) tag with Grade 5 titanium (Ti) shafts and petals (Fig. 5a) (Andrews *et al.* 2008) was deployed for post-disentanglement tracking (1237). The dart shafts were 0.4 cm in diameter, with a penetration of 6.7 cm, including the cutting tip, with a length of 1.2 cm and a maximum width of 0.6 cm. Each shaft had two rows of petal barbs welded to the shaft, 1.93 cm long, in an elongated tear-drop shape. The petal was narrowest at the base, measuring 0.305 cm wide and it was 0.533 cm at its widest point. The petals were cut from Ti sheet that was 0.0406 cm (0.016 in.) thick.

After the tag was deployed, the sedation and reversal darts were recovered by gently pulling on tethers that were trailing behind the whale. Attempts were made to recover the two antibiotic darts, but the tethers separated from the darts when they were pulled. It was unclear at the time if the antibiotic injection needles remained in the animal. The animal was observed for a further 2 h visually, and then tracked *via* the LIMPET tag.

The whale was observed dead at sea on 1 February 2011 by an aerial survey team. It was towed ashore on 2 February and a necropsy was conducted on 3 February, using standard necropsy protocol as previously described (McLellan *et al.* 2004). During the necropsy, the remaining entangling line was systematically removed, photographed and the orientation of the gear on the animal was described. Lesions in skin, blubber, muscle, and skeleton were systematically labeled, carefully examined, photographed and dissected as appropriate and histopathology samples preserved in 10% neutral buffered formalin, processed routinely for sectioning and hematoxylin and eosin staining, and then examined using routine bright field microscopy.

The force required to induce an 80º bend with an outer radius of 20 mm was measured using a jig comprised of the needle passing through nylon and then rubber blocks, to model blubber and muscle respectively. A crane and heavy anchor were then respectively applied to the blocks and the force required to induce the bend measured.

Figure 3. (a) Paxarms whale dart with tether and float. (b) Excised blubber block section in the plane of retained needle implantation in right whale #3911. Note the defect caused by the needle conforms closely to the needle shape, suggesting it was firmly fixed in the blubber. The proximal bend was caused by dart body water drag and towing the whale onto shore. The distal bend was at the muscle blubber interface penetrating the muscle and creating the cavity described in the text. (c) Cavity in muscle of right whale #3911 caused by bent retained needle tip (1), initially bent by needle tip embedded in intact muscle shearing relative to overlying blubber. Muscle underlying bent needle tip has been reflected to the top of the page along the white line. A rectangular section of subdermal sheath has been dissected (2), slid off the needle tip, and reflected to the bottom of the page. The cavity, cut into the muscle by the needle tip, as described in the text, spans the width and height of the image above the scale marker (white asterisks). Note the dimensions of the cavity exceed twice the bent needle tip length suggesting movement of the muscle relative to the overlying blubber. Cranial is to left of the image. Scale marker in cm and in.

Figure 4. (a) Spring-loaded knife for cutting embedded rope on entangled large whales. (b) Stab wound from spring loaded knife in right whale #3911. A section from the wound has been dissected and is shown in side view at bottom.

Results

The average minimum speed over the entire LIMPET tag tracking period of 6 d was 2.7 knots with a range of 1.3–5.0 knots, with no obvious trend with time, thus verifying the animal survived the sedation and disentanglement activity. Satellite transmissions ceased on 21 January 2011, 6 d post-attachment.

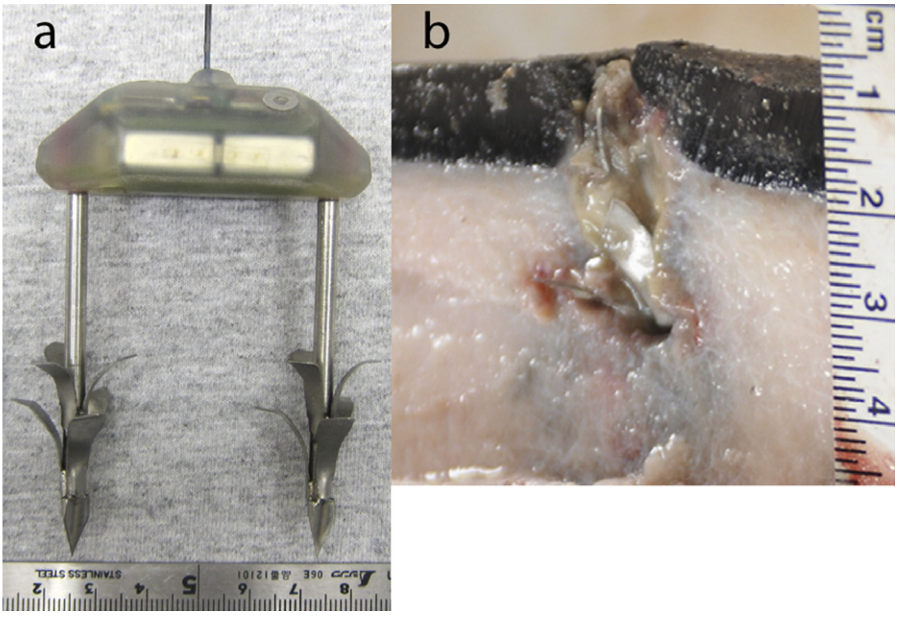

Figure 5. (a) LIMPET tag with titanium barbs welded to shafts. Distance between the shaft points is 5 cm. The tag body rests on the skin surface with the shafts and petals embedded in the blubber. (b) LIMPET tag shaft stab wound in right whale #3911 with retained petals and purulent exudate. Scale markers = cm.

Detailed descriptions and illustrations of the pathology encountered at necropsy are in the necropsy report (McLellan and Costidis, unpublished necropsy report). Those findings are summarized here. The 10 m female right whale was in a moderate state of decomposition. Histologically there was bacterial overgrowth in the integument characterized by the presence of postmortem bacilli. There was mild to moderate autolysis of internal organs characterized by loss of cellular detail, postmortem bacterial overgrowth, and postmortem gas formation.

The dorsal axillary blubber was 6.5 cm in depth. There were multiple entanglement wounds: rope laceration of the oral rete; 12 mm (5/16") 3 strand rope embedded in the dorsal aspect of the right lip (Fig. 6), that was fully buried beneath thickened white epidermal scar tissue (histological findings included myofiber atrophy, edema and fibrosis); and deep rope laceration encircling both flippers, but more loosely on the left. There was a large looping section of line interwoven between the baleen plates of each side of the oral cavity crossing at the base of the tongue and possibly entering the proximal esophagus.

Numerous shark bites caused major tissue defects in the tail flukes and peduncle. One deep bite to the peduncle severed the caudal vein with suspected hemorrhage as seen with tissue color change and edema in surrounding tissues. Histologically, edema was observed in one shark bite sample site. There was no evidence of hemorrhage or inflammatory cells. However, given that these bite wounds were exposed vascular areas, loss of blood and cellular washout could

Figure 6. Cross section of right lip of right whale #3911 with embedded rope.

have occurred limiting the complete microscopic features. The shark bites described on the peduncle were likely perimortem; postmortem predation also occurred given that a 4.6 m white shark, *Carcharodon carcharias*, was photographed feeding on the carcass over two days.

Broadhead cutter lesions (made on 29 December 2010) appeared as incomplete, cruciform, shallow incisions from 0 to 7 mm into the blubber (Fig. 2b). Overlying epithelium was absent in this region following postmortem loss.

Spring-loaded knife lesions (made on 15 January 2011, Fig. 4b) were up to 4.5 cm wide, 15.5 cm long, and 5 cm deep. Histologically, within the superficial dermis around these lesions, there were abundant viable and degenerate neutrophils and fewer foamy macrophages. Bacterial cocci were present within the center of the neutrophilic infiltrate and occasionally within macrophages. Fibrin thrombi filled superficial dermal vessels and there were loosely organized fibroblasts within the dermis.

At the LIMPET tag attachment site we found two stab wounds 5 cm apart approximately 1 m to the left of the dorsal midline and 2 m caudal to the flipper insertion. The tag and attachment dart shafts were absent. A block of skin and blubber including the attachment site was excised and the two stab wounds were dissected by 7 mm serial slices of the blubber block at a 90º angle to the skin surface (Fig. 5b). The wounds penetrated at an oblique angle to the skin surface, so the slices cut through the wounds at an angle. Tag petal barbs were encountered within and adjacent to the stab wound lumen, surrounded by a purulent exudate. Barbs could be extracted with gentle traction. The barbs separated from the shaft just above the weld points. Histologically the tracts were filled with viable and degenerate neutrophils, fewer macrophages, and cellular debris within a fibrinous matrix. Bacterial cocci were in dense colonies within the inflammatory infiltrate. Fibroblasts were present singly or in small aggregates. Dermal hemorrhage was evident and there were fibrin thrombi within vessels. At the site of tag implantation, there was disruption and rounding of the epidermis. All layers including the stratum externum, stratum intermedium, and stratum basale adjacent to the implantation site exhibited cytoplasmic swelling and pallor. There was mild neutrophilic exocytosis through the epidermal layers. Pigmentation was reduced within the stratum basale. In the superficial dermis (papillary dermis), there were neutrophils, few fibroblasts, and increased numbers of capillaries lined by plump endothelial cells (neovascularization).

Three of the four injection sites were not found, despite an extensive search of the relevant body surfaces with serial slicing of the underlying blubber. After examination of the ventral and right lateral aspect of the animal, it was rolled over. An exposed whale dart needle (from the second antibiotic dart) was embedded in the left dorsolateral aspect of the abdominal region approximately 1 m anterior to the genital slit. The proximal 9 cm of the needle, which had shed the hub and syringe barrel, were exposed and bent into a slight craniad curve with an underlying furrow craniad from the insertion suggesting contact with the beach while being hauled tail first on retrieval. Just deep to the site of penetration of the epidermis a more substantial 80º bend could be observed, suggesting that the needle had been pushed in further while laying on its left side on the beach. An epidermal furrow pointing caudad was suggestive of the syringe body having laid flat along the body after the needle bent by drag from the syringe body while swimming. The complex superficial bend in the needle mirrored these two furrows. Numerous smaller lacerations radiating from the needle penetration point were consistent with a needle shaft that was forcefully manipulated back and forth. This is consistent with a needle exposed to internal shearing forces. A second 80º bend was present at the level of the subdermal sheath (Fig. 3b, c). (This needle is Accession No. 2012.4.2 at the New Bedford Whaling Museum, 18 Johnny Cake Hill, New Bedford, MA). Bloody edema and blood clots were present between the hypodermis and subdermal connective sheath as well as between the subdermal connective sheath and epaxial muscle fascia. The 80º bend at the interface between blubber and muscle could not have been caused by external manipulation without generating much deeper wounds in the blubber. This bend, 10 cm from the distal needle point, was strongly suggestive of shearing forces between the muscle and blubber as the etiological factor. The wound margins of the subdermal connective sheath at the wound track had pale to dark red discoloration consistent with recent hemorrhage (Fig. 3c). Radiating outward from the wound track was purple to gray discoloration consistent with resolving hemorrhage. These findings suggested an older resolving injury at the periphery of the wound track, with more recent or continued injury immediately surrounding the needle. The epaxial muscle deep to the needle penetration point had an elliptical region approximately 29 cm (craniocaudal) $\times$ 20 cm (latero-medial) (Fig. 3c) containing bunched and curled muscle fibers with a shredded appearance. Numerous small and large, loose and adherent well formed blood clots were present within and around the muscle cavity and in close proximity to the needle tip.

Histological analysis of the retained needle site showed the following. Adjacent to the dermal collagen, laminar bands of fibrocytes were separated by small to moderate amounts of collagen and a dense band of extravasated erythrocytes (hemorrhage) separated by thin tendrils of fibrin. Within sections of fibroadipose, there was multifocal fibroplasia characterized by streaming fibrocytes and interspersed vascular channels (neovascularization). There was collapse of adipocytes which were deeply basophilic (saponification). Abundant foamy macrophages and fewer neutrophils infiltrated the adipose. In the muscle there was a dense coagulum of hypereosinophilic myofibers with pyknotic nuclei (coagulative necrosis) and hypereosinophilic collagen (collagenolysis) with interspersed neutrophils, macrophages, and fewer lymphocytes and plasma cells. Small vascular channels, primarily venules, were filled with fibrin.

The force required to achieve the observed bend in the needle at the subdermal sheath was measured at 250 kg.

Discussion

The thin blubber layer and visual observations suggest that this was a chronically emaciated animal prior to disentanglement, sedation and tagging. This, along with the severe rope lacerations and chronic embedment in soft tissue and flippers observed at necropsy suggest that the demise of the animal was precipitated by chronic entanglement. The looping line in the caudal oral cavity that possibly entered the esophagus suggested the animal could not feed effectively. Perimortem shark bites into large peduncle vessels suggest its ultimate demise was a result of severe blood loss, though the interplay of all factors is supposition at this stage.

Management of chronic severe entanglements brings inevitable compromises between risk from intervention methodologies and the potential benefit of disentanglement for the animal. The first invasive tool deployed in this case was the broadhead cutter. The superficial lesion documented here secondary to its use (Fig. 2b) would seem to be relatively insignificant and not life threatening. This tool has a similar penetration and nonpersistence to most biopsy tools in use today.

The cellular response associated with the LIMPET tag is consistent with a retained foreign body with sustained contamination by nonsterile sea water (Geraci and Smith 1990). Longer survival of the animal would likely have resulted in shedding of the tag remnants. There was no evidence of abscessation beyond the immediate area of the foreign bodies. The discontinuation of the tag transmission 6 d after deployment was thought to have resulted from failure in situ, shedding, rubbing the system on the bottom, or the animal dying, bloating, and rolling such that the tag was submerged and could no longer transmit. The absence of the tag on retrieval of the carcass could be consistent with any of the above scenarios, in that it could have been present, unless shed earlier, until hauled up the beach, when the drag on the sand broke off the petals in situ and shed the tag. It is therefore unclear if the animal died when the tag ceased transmitting. The tag data show that the animal lived for at least 6 d post sedation and disentanglement and that during this time it moved at rates consistent with recovery from sedation. The mean speed was marginally faster than the range of speeds reported for tagged North Atlantic right whales (Mate *et al.* 1997). Thus the LIMPET tag, while not present at necropsy, 11 d after it ceased transmitting, nonetheless provided critical information about the survival of the animal in the days following sedation.

The spring-loaded knife was used to great effect in removing all accessible constricting rope after the animal had been sedated. Multiple superficial stab wounds were however the consequence of this action. None of the wounds were deeper than the designed maximum depth (6 cm), which was less than the blubber depth of even this young emaciated right whale. Right whales have fully healed from far more severe wounds from other sources, such as propeller incisions. It would therefore seem to be a disentanglement tool worth retaining and using to remove entanglements that cannot be effectively resolved with noninvasive tools.

Three darts showed no evidence of acute tissue reaction. The retained fourth needle induced a predictable stab wound through the skin and blubber. All sedation darts deployed to date have been seen to bend at the skin surface from the water drag on the syringe barrel within an hour of implantation in a swimming right whale. An additional bend at the skin surface resulted from friction between the beach and the needle site in the whale. In contrast, the second bend at the subdermal sheath and the underlying muscle cavity was not predicted. Bunched and curled muscle fibers along the muscle cavity margins and present loose within the cavity (Fig. 3c), were assumed to be typical of antemortem shredding, as seen in antemortem watercraft impacts with blunt force traumatic shredding of muscle (Lightsey *et al.* 2006, Rommel *et al.* 2007). Additionally, all blood clots examined had the appearance of relatively fresh clots, without any resolution or reaction to them or the surrounding damaged tissue. Despite emaciation possibly inducing a delayed healing response, this suggests either an acute or progressive traumatic event not explained by damage sustained at the time of injection, which was at least 6 d before the animal died.

The risk of an intramuscular needle bending in this manner, following movement of muscle under the blubber has been shown for captive cetaceans, such as dolphins or killer whales given intramuscular injection. Two bends have been seen in a needle if the animal is moving during insertion and removal. [3] There appears to be less bending of the needle with injections given at the level of the dorsal fin for these species. This may be related to the degree of displacement of the muscle mass relative to the anatomic site of insertion, and penetration of the needle through internal muscle tendons that vary in depth and location. Increasing the drag of the dart tether buoys in water, while keeping their ability to fly in air without breaking the tether, may allow for more likely removal soon after deployment to decrease dart needle tissue displacement and damage. These darts fully inject their dose within a few seconds. Thus devices deployed further forward and towards the dorsal midline may show less cavitation. Experimental manipulation of cetacean cadavers with implants through blubber into muscle at different locations could test this hypothesis.

The epaxial muscle cavitation observed was likely the result of a combination of factors including direct physical damage from pivoting and levering of the needle itself, hydrostatic damage from the fluid pressure during the injection, and chemical damage from the antibiotic treatment. The elliptical nature of the cavity suggests that the primary cause of the muscle damage was due to physical damage from the needle being fixed in the blubber, while the muscle moved back and forth during normal propulsive tail movements. The 29 cm cranio-caudal dimension of the cavity exceeds the potential 10 cm radius circle that could have been scribed by the needle rotating *in situ* by 9 cm, given that the needle was fixed in the blubber wall. Furthermore it is very unlikely that the needle was able to fully rotate, given that the oblique angle of entry through the blubber would mean that as the needle rotated, the tip would interfere with the base of the blubber cranially. Thus the muscle moved rela-

[3] Personal communication from Michael Walsh, College of Veterinary Medicine, University of Florida, Gainesville, FL 32610, 3 October 2011.

tive to the blubber by at least 4 cm cranially and caudally at this point of the body and probably much more. The cavity could have formed in part by the chemical and hydrostatic effects of the antibiotic injection. However, drug-related factors including physical (volume) and chemical composition do not sensibly account for the fresh hemorrhage, six or more days after injection. It is also unlikely that seawater ingress was involved, in that the needle ports were blocked with tissue fragments on retrieval, and blubber was tightly compressed around the needle shaft. Perhaps more telling than these observations is the primary observation that the initial bend in the needle at the blubber muscle interface was to 80^{o} and at a point 9 cm from the tip. This requires the muscle to have moved about 8 cm relative to the blubber to create the bend observed. This could only have occurred peracutely very shortly after insertion, when the bending force was greatest, prior to significant muscle damage. It is interesting that all four darts were deployed in the same general area and only one was retained. These darts and needles have been deployed on 20 occasions including the previously described sedation attempt (Moore *et al.* 2010) and for antibiotic treatment (Gulland *et al.* 2008). Needle bends were observed during system development trials, but they were at the skin surface, where the momentum of the filled syringe bent the syringe body forward, kinking the needle at its hub. This problem was resolved by adding a carbon fiber liner to the needle, creating a more resilient structure.

The observation of this muscle cavity, and the initial needle bend, has potential relevance for the use of any rigid device that penetrates the blubber-muscle interface. Study of the resighting of animals tagged with such implanted devices whose antennae remain in the overlying water, has not shown any evidence of reduced survival (Best and Mate 2007). However, in a recent review Walker *et al.* (2011) concluded that "major gaps exist in understanding whether marking devices impede natural behaviours such as movement and feeding patterns, growth, and health, and whether marine mammals experience pain and distress during and after marking." We are bound, therefore, to consider not only survival but also individual animal health effects and welfare (Fraser *et al.* 1997). Beyond postimplantation photographic survey of the surface of implanted tag sites, there has been little to perhaps no opportunity to examine the host response to, or animal welfare aspects of, implanted foreign bodies with various hold-fast designs that are bathed in seawater proximally, and inserted through stab wounds in skin, blubber and muscle in wild cetaceans. While such tags are more robust than the whale dart needle described here, and they are thus unlikely to bend, the tags, like the needle bent into an effective barb, have barbs, in their case designed to retain the tag in the muscle, fetching up on the relatively robust subdermal sheath. Therefore if they are implanted in a part of the body with comparable muscle movement relative to the overlying blubber, they may create a craniocaudal slot as wide as the diameter of the tag, as deep as the tag's protrusion into the muscle and of perhaps 8 cm in length or more. Lateral movement is likely as well, thus the slot may become an ellipse. It is difficult to know quite how painful such a constant swimming induced, cyclic laceration of muscle over a tag tip would be until the tag is rejected, but these observations would seem to be pertinent when use of such devices is being considered during project permitting and animal care and use protocol review.

The observation of a single bent needle could perhaps be dismissed. More information is needed in different age groups and species. However it suggests a reasonable mechanistic basis for the many chronic depressions observed at the site of satellite tag implantation (Mate *et al*. 2007). These may result from skin and blubber being depressed into the underlying void created by the cavity in the muscle moving back and forth past the tag tip and barbs. The clean stab wound illustrated in Fig. 3b would suggest that there is more to these depressions than being caused by rupture of fat cells in the blubber layer where tags enter (Mate *et al*. 2007).

In conclusion the intervention with sedation, and the required tagging needed to evaluate sedation, disentanglement and the outcome of chronic severe entanglement, can result in a number of potential complications during the application of these techniques. Further development is warranted based on the demonstrated benefits during difficult and potentially lethal right whale disentanglements. Despite new interventions that removed much of the external entanglement, gear remained in the whale's mouth that limited the animal's ability to feed properly. The data are all from a single case, but the findings also question whether penetration of the cetacean subdermal sheath, with persistence of rigid foreign bodies fixed in blubber and penetrating into mobile muscle, is an appropriate experimental protocol in terms of the welfare of an individual. Such tools for therapeutic intervention, which in many cases may be lifesaving, should be designed and deployed to minimize retention. Post intervention monitoring and postmortem examination of this animal has greatly helped in clarifying variables and intervention protocols for future improvement and application to severely entangled large whales. However, if monitoring by tag is needed, the needle data suggest that tags should be used which do not add trauma in the axial muscle layers. But more than anything, fishery mitigation efforts should continue to focus on policies that prevent entanglements from occurring.

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Literature Cited

Andrews, R., R. Pitman and L. Ballance. 2008. Satellite tracking reveals distinct movement patterns for Type B and Type C killer whales in the southern Ross Sea, Antarctica. Polar Biology 31:1461–1468.

Best, P., and B. Mate. 2007. Sighting history and observations of southern right whales off South Africa. Journal of Cetacean Research and Management 9:111–114.

Cassoff, R. M., K. M. Moore, W. A. McLellan, S. G. Barco, D. S. Rotstein and M. J. Moore. 2011. Lethal entanglement in baleen whales. Diseases of Aquatic Organisms 96:175–185.

Fraser, D., D. M. Weary, E. A. Pajor and B. N. Milligan. 1997. A scientific conception of animal welfare that reflects ethical concerns. Animal Welfare 6:187–205.

Geraci, J. R., and G. J. D. Smith. 1990. Cutaneous response to implants, tags, and marks in beluga whales, *Delphinapterus leucas*, and bottlenose dolphins, *Tursiops truncatus.* Advances in research on the beluga whale, *Delphinapterus leucas*. Canadian Bulletin of Fisheries and Aquatic Sciences 8:1–95.

Gulland, F. M. D., F. Nutter, K. Dixon, *et al.* 2008. Health assessment, antibiotic treatment, and behavioral responses to herding efforts of a cow-calf pair of humpback whales (*Megaptera novaeangliae*) in the Sacramento River Delta, California. Aquatic Mammals 34:182–192.

Johnson, M., and P. Tyack. 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. IEEE Journal of Oceanic Engineering 28:3–12.

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 Management (Special Issue) 2:193–208.

Lightsey, J. D., S. A. Rommel, A. M. Costidis and T. D. Pitchford. 2006. Methods used during gross necropsy to determine watercraft-related mortality in the Florida manatee (*Trichechus manatus latirostris*). Journal of Zoo and Wildlife Medicine 37:262–275.

Mate, B. R., S. L. Nieukirk and S. D. Kraus. 1997. Satellite-monitored movements of the northern right whale. Journal of Wildlife Management 61:1393–1405.

Mate, B., R. Mesecar and B. Lagerquist. 2007. The evolution of satellite-monitored radio tags for large whales: One laboratory's experience. Deep-Sea Research 54:224–247.

McLellan, W. A., S. A. Rommel, M. J. Moore and D. A. Pabst. 2004. Right whale necropsy protocol. Final Report to NOAA Fisheries for contract #40AANF112525. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, NOAA Fisheries Service, 1315 East West Highway, Silver Spring, MD. 51 pp.

Miller, C., P. Best, W. Perryman, M. Baumgartner and M. Moore. 2012. Body shape changes associated with reproductive status, nutritive condition and growth in right whales *Eubalaena glacialis* and *Eubalaena australis*. Marine Ecology Progress Series 459:135–156.

Moore, M., A. Knowlton, S. Kraus, W. McLellan and R. Bonde. 2004. Morphometry, gross morphology and available histopathology in Northwest Atlantic right whale (*Eubalaena glacialis*) mortalities (1970 to 2002). Journal of Cetacean Research and Management 6:199–214.

Moore, M. J., A. Bogomolni and R. Bowman, *et al.* 2006. Fatally entangled right whales can die extremely slowly. Proceedings Oceans'06 MTS/IEEE-Boston, Massachusetts, 18–21 September 2006. 3 pp. Available at http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4098947

Moore, M., M. Walsh, J. Bailey, et al. 2010. Sedation at sea of entangled North Atlantic right whales (*Eubalaena glacialis*) to enhance disentanglement. PLoS One 5:e9597.

Pettis, H. 2010. North Atlantic Right Whale Consortium 2010 annual report card. Available at http://www.narwc.org/pdf/2010_report_card_addendum.pdf

Rommel, S. A., A. M. Costidis and T. D. Pitchford. 2007. Methods for characterizing watercraft from watercraft-induced wounds on the Florida anatee (*Trichecus manatu latirostris*). Marine Mammal Science 23:110–132.

Schorr, G. S., R. W. Baird, M. B. Hanson, D. L. Webster, D. J. McSweeney and R. D. Andrews. 2009. Movements of satellite-tagged Blainville's beaked whales off the island of Hawai'i. Endangered Species Research 10:203–213.

U.S. Federal Register. 2007. Taking of marine mammals incidental to commercial fishing operations; Atlantic Large Whale Take Reduction Plan regulations. FR 72 (193):57104–57194 (5 October 2007). National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Department of Commerce, Washington, DC.

Walker, K. A., A. W. Trites, M. Haulena and D. M. Weary. 2011. A review of the effects of different marking and tagging techniques on marine mammals. Wildlife Research 39:15–30.

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