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Original Article

Longline hook testing in the mouths of pelagic odontocetes

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Several species of odontocete cetaceans depredate bait and catch and, as a result, become hooked and entangled in pelagic longline fisheries. The present study measured how selected commercial longline hooks, including "weak hooks", behaved within odontocete mouths. Five hooks (Mustad-16/0, Mustad-18/0, Mustad J-9/0, Korean 16, and Korean 18) were tested on three species of odontocetes known to interact with longline fisheries—short-finned pilot whales (*Globicephala macrorhynchus*), Risso's dolphins (*Grampus griseus*), and false killer whales (*Pseudorca crassidens*). Specimens were secured to a stanchion, hooks were placed in the mouth at multiple positions along the dorsal lip, and the force required to pull each hook free was measured. The soft tissue lips of these odontocetes were capable of resisting forces up to 250 kg before failing. The polished steel M-16, M-18, and J-9 hooks straightened at forces between 50 and 225 kg, depending on hook gauge. When straightened, these hooks exposed the sharpened barb, which sliced through the lip tissue, usually releasing the hook intact. The K-16 and K-18 hooks behaved very differently, breaking at higher forces (110–250 kg) and consistently just at the barb; usually, there was measurable soft-tissue loss and often shards of the hook were retained within those soft tissues. The different behaviours of these two hook types—the M and J type polished steel vs. the K type carbon steel—were consistent across all species tested. Mechanical tests were also conducted to determine if hooks could fracture the mandible of these same odontocetes. Only the M-18 and K-18 hooks had sufficiently large gapes to hook around the mandible, and both hook types fractured bone in short-finned pilot whales and Risso's dolphins. These results support other lines of evidence indicating that longline hooks can cause serious injury to these species, and suggest possible steps to mitigate these impacts.

Keywords: conservation, longline hooks, odontocete, serious injury, tissue testing, weak hooks.

Introduction

Several species of odontocete cetaceans depredate fishery bait and catch and, as a result, become seriously injured within, pelagic longline fisheries (reviewed by Hamer *et al.*, 2012). For example, from 1992 to 2008, 83 short-finned pilot whales (*Globicephala macrorhynchus*) were determined to be seriously injured (likely fatally), and five individuals died, as a result of interactions with the Atlantic US pelagic longline fishery (Waring *et al.*, 2012). Eighteen false killer whales (*Pseudorca crassidens*) were determined to be seriously injured, and one individual died, through interactions with the Hawaiian pelagic longline fishery from 2006 to 2010 (Waring *et al.*, 2012). The present study focused on measures that would reduce the serious injury of large odontocetes after they become hooked by pelagic longline gear, by testing how various hooks, including "weak hooks", behave within the soft and hard tissues of the odontocete mouth.

Weak hooks are formed from bent wire that is circular in cross section, while traditional forged strong hooks are oval in cross section (Kerstetter, 2012). Weak hooks are designed to exploit differences in size (and, thus, hypothesized strength) of target (e.g. tuna, swordfish) and non-target (e.g. large odontocetes) species in pelagic longline fisheries (e.g. Bayse and Kerstetter, 2010). Recent studies suggest that the use of weak hooks has little effect on the catch of target fish species but does result in the retrieval of more straightened hooks from the fishery (Bayse and Kerstetter, 2010; Bigelow *et al.*, 2012; Kerstetter, 2012). These are promising results, but there is little empirical information on the interaction between odontocetes and weak hooks because of the very low catch rates of these non-target species in commercial fisheries and the difficulty of observing these interactions at close quarters (Bigelow *et al.*, 2012; Hamer *et al.*, 2012). Other research has described how fishing gear interacts with cetacean soft tissues and has yielded important insights that can be used to identify, and, thus, potentially mitigate the impacts of such entanglements (e.g. Winn *et al.*, 2008; Barco *et al.*, 2010).

The present study directly measured how selected longline hooks, including "weak hooks", behaved within the odontocete mouth. The cetacean species tested—short-finned pilot whales, Risso's dolphins (*Grampus griseus*), and false killer whales—are known to engage in depredation and represent some of the most commonly taken species within pelagic longline fisheries in the western North Atlantic (Bayse and Kerstetter, 2010; Kerstetter, 2012; Waring *et al.*, 2012) and Hawaiian Pacific (Forney and Kobayashi, 2007; Bigelow *et al.*, 2012; Waring *et al.*, 2012). Two types of mechanical tests were conducted utilizing stranded odontocete specimens. The first was designed to investigate how hooks interact with the soft tissues of the odontocete lip, and the second was designed to determine whether longline hooks could fracture the odontocete mandible. The results of these novel experiments provide biological guidance for identifying potential hook designs, including commercially available "weak hooks", which could minimize the potential for serious injury in these odontocete species.

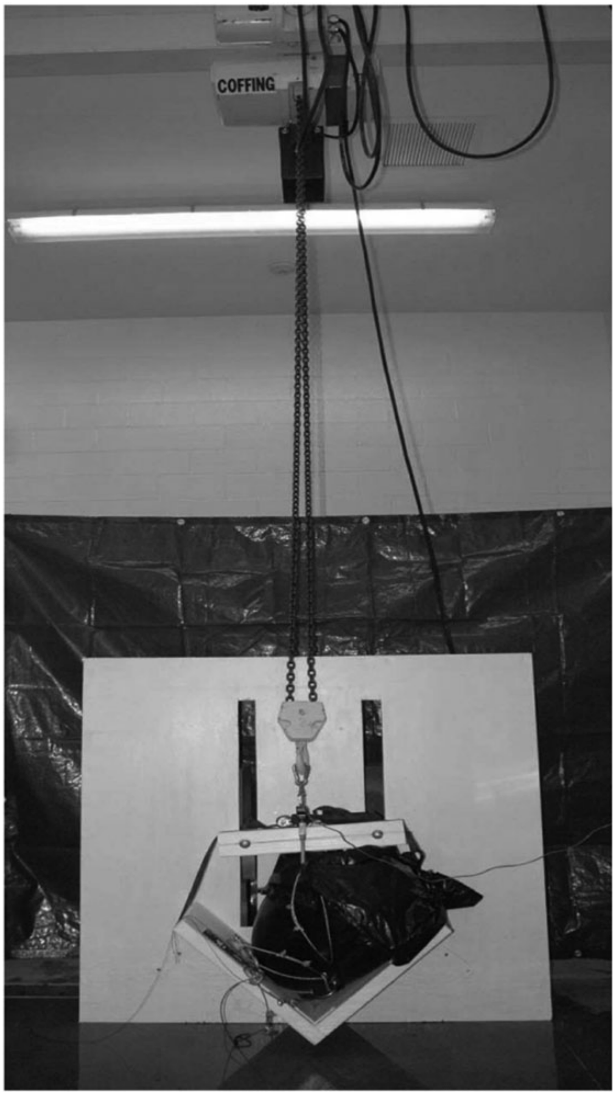

Figure 1. Set-up of testing apparatus with overhead crane supplying force, in-line load cell (sample rate 28 Hz), and a short-finned pilot whale head (KLC 111) secured in stanchion. Heavy cement weights were added to the back of the stanchion and are not visible in the image.

Methods

A specialized testing stanchion was constructed to firmly secure and support entire heads of stranded pelagic odontocetes for hook and tissue deformation tests (Figure 1). Heads were strapped onto the stanchion, which was secured to the floor with weights. Weights were added after initial tests on short-finned pilot whale KLC 111 demonstrated additional weight was required when testing heavier gauge hooks. The orientation of each head could be varied to provide multiple pulls of the hooks in both a dorso-caudal and ventro-caudal direction. These force vectors were designed to mimic the pulling a pelagic odontocete would apply to a hook and gangion on main line of a commercial longline fishery. Force was applied with a 2 t overhead crane that pulled at a rate of 4 cm s^{-1}, and transmitted to the hooks through a braided steel cable secured with small cable binders. For human safety during experiments, the crane operator wore a protective face shield and stood behind the stanchion, and all other personnel observed from within an adjacent, closed computer lab. Forces were recorded with an MLP-1000 in-line load cell (Transducer Techniques,

Table 1. Reference for measurements of the five hook types investigated in this study (see Figure 2 for measurement descriptions).

Hook type	Total length (mm)	Gape (mm)	Bite (mm)	Gauge (mm)	Weight (g)
M-16	62	25	38	3.6	12
M-18	75	30	45	4.9	26
J-9	74	27	36	4.8	16
K-16	60	25	30	4.5	17
K-18	76	24	39	5.1	26

"Gauge" is the thickness of the wire used to manufacture the hook.

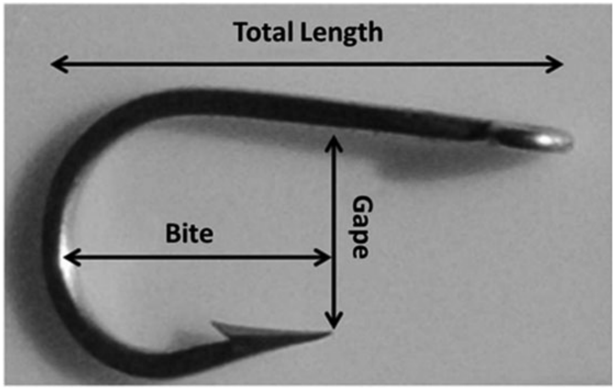

Figure 2. Image of a J-9 straight hook and identification of each measurement described in Table 1.

Table 2. Odontocete cetacean specimens used in the study.

Common name	Species	Field #	Sex	TL (cm)	TM (kg)	Age class
Short-finned pilot whale	*Globicephala macrorhynchus*	KLC 111	F	244	179	Subadult
Short-finned pilot whale	*Globicephala macrorhynchus*	CAHA 093	M	269	334	Subadult
Risso's dolphin	*Grampus griseus*	KLC 136	F	254	163	Adult
Risso's dolphin	*Grampus griseus*	KLC 123	M	276.5	256.5	Adult
False killer whale	*Pseudorca crassidens*	KLC 053	F	432	N/E	Adult

All specimens were collected as fresh strandings in North Carolina, transported to UNCW and remained frozen at −20°F until thawed for experimentation.

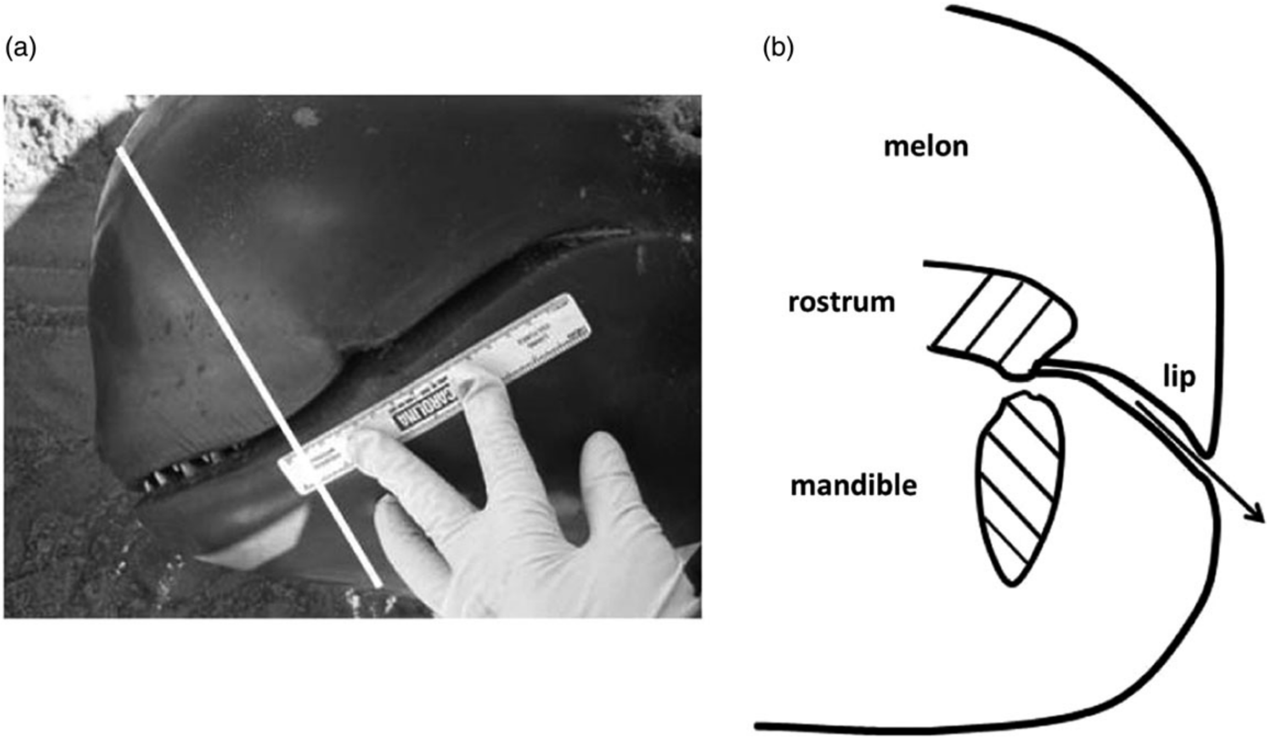

Figure 3. Anatomic features of odontocete head. (a) Left lateral view of a stranded short-finned pilot whale with dorsal lip defect characteristic of longline gear hooking interaction. White line denotes the level of the cross section depicted in b. (b) Schematic of cross section through the head showing the bone (hatched) and soft tissue lip. During tests, longline hooks were secured on the inner broad surface of the dorsal lip, or around the lingual (medial) surface of the bony mandible. The arrow denotes the path the gangion would exit the lip drawing the hook through the thin cavity between the dorsal and ventral lip. As the hook is pulled through the cavity, it is easily caught in soft tissue and becomes "hooked".

Temecula, CA, USA; sampling rate 28 Hz), positioned in-line between the hook and the overhead crane, and directly downloaded (DPM-3-DLS software, Transducer Techniques) in real time to a laptop computer for later analysis.

Circle hooks that were tested included "weak hooks" Mustad 16/0 (#39988D) and Mustad 18/0 (#39960D; O. Mustad and Sons A.S., Gjövik, Norway), and standard commercial carbon K-16 and carbon K-18 hooks, produced in South Korea and known within the fishery as "Korean hooks" (see Table 1 and Figure 2 for a complete suite of hook measurements). The choice of these hooks was made in consulation with Dr David Kertstetter at Nova Southeastern Univeristy. Additional discussions with members of the Pelagic Longline Take Reduction Team (PLTRT; http://www.nmfs.noaa.gov/pr/interactions/trt/pl-trt.htm) resulted in the addition of the Mustad J 9/0 (#7698B) hook. Multiple tests of each hook type were conducted to determine its mechanical behaviour in the selected odontocete species.

All odontocete specimens utilized in this study had live-stranded in the Outer Banks of North Carolina, and had subsequently died or been euthanized (Table 2). Heads were collected whole, frozen at −20°F (usually within 12–24 h), and thawed in water just before experimentation and were in fresh condition. Short-finned pilot whales (*G. macrorhynchus*) are taken in longline fisheries off the Outer Banks of North Carolina (Waring *et al.*, 2012; PLTRT website http://www.nmfs.noaa.gov/pr/interactions/trt/pl-trt.htm). Risso's dolphins (*G. griseus*) are also taken in pelagic longline fisheries off the northeast coast of the US (Waring *et al.*, 2012; PLTRT website http://www.nmfs.noaa.gov/pr/interactions/trt/pl-trt.htm). False killer whales (*P. crassidens*) have not been documented as bycatch in longline fisheries in the Atlantic, but this rare stranded specimen was included to assist in conservation efforts of the False Killer Whale Take Reduction Team in the Pacific.

Hooks were tested one at a time and placed in two anatomical positions in the odontocete mouth—within the soft tissue of the

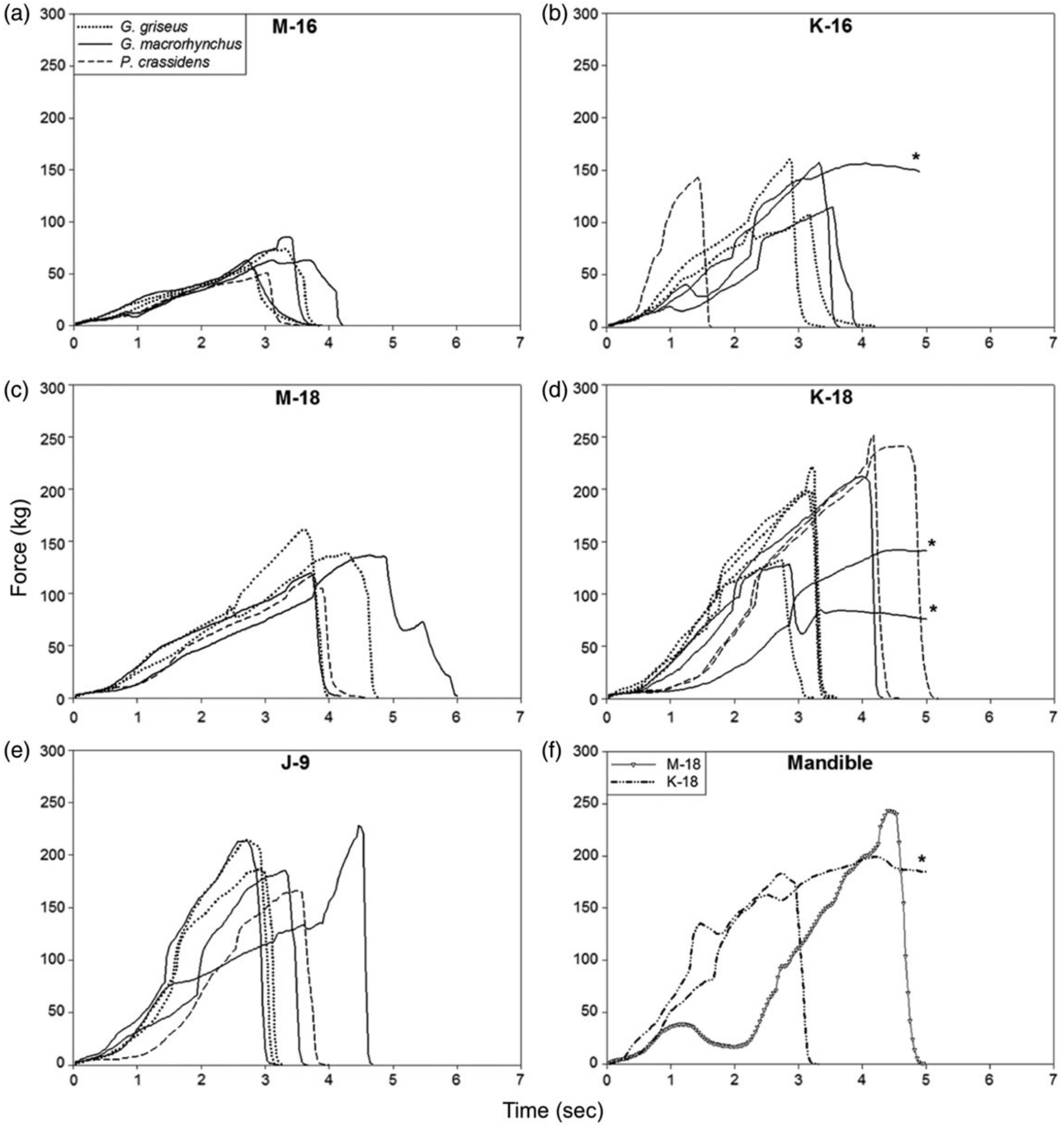

Figure 4. Longline hook behaviour within the soft tissue lips (a–e) and around the lingual surface of the mandible (f) for all hook types and specimens tested. *For short-finned pilot whale KLC 111, four tests (one K-16 and two K-18 in soft tissue and one K-18 in mandible) terminated, while hooks were still loaded and in tissue, as there was insufficient weight to keep stanchion secured to the floor.

dorsal lip or around the lingual (medial) surface of the mandible (Figure 3). Hooks were placed in series at multiple positions along the dorsal lip, to increase the number of tests that could be conducted on each specimen. Before each experiment, notes on the anatomical placement of the hook, and a photograph of its position *in situ*, were taken. Following the test, how the hook was released from the tissue (e.g. hook straightened and sliced through tissue, hook shattered, non-deformed hook tore through tissue) and the type of tissue damage caused (e.g. soft tissue laceration, bone fracture) were recorded, and the test site was photographed. For mandibular tests, the heads were subsequently dissected to document injury to the bone and surrounding tissues. Each hook was also photographed post-test to visually record how it deformed (or not) during experimentation. No photographs were taken during tests for safety reasons.

Data from the MLP-1000 in-line load cell were downloaded into Excel (Microsoft Office, 2010), visually inspected, and graphed using Sigma-Plot (Systat Software Inc., Version 11.0). The present study is descriptive in nature, so the results of all completed tests are presented graphically. In addition, linear regression analysis was used to quantitatively characterize and compare the mechanical behaviour of the Mustad vs. Korean circle hook types during the loading portion of the soft tissue tests.

Results

Longline hook behaviour within the soft tissue of the odonotcete dorsal lip

The first goal of the study was to investigate how hooks interacted with the soft tissues of the odontocete lip, and each hook type was tested in each species (Figure 4a–e). Overall, the forces required to pull the hooks through the soft tissue lip were more dependent upon the hook type than upon the species or upon hook position along the lip. The Mustad weak hook M-16, with the smallest gauge wire of any hook tested (Table 1), released from the lip at the lowest forces (51–85 kg), while the Korean carbon K-16 hook (0.9 mm wider gauge wire), sustained maximum forces of 108–161 kg before release. Similarly, the weak hook M-18 released at loads between 118 and 162 kg, while the K-18 (0.2 mm wider gauge wire) sustained maximum loads of 132–251 kg. The J-9 hook sustained loads of between 166 and 228 kg.

The loading curves of the Korean K-16 and K-18 hooks were much more variable than those of the weak hooks M-16 and M-18 (Figures 4 and 5), which appeared to reflect the very different mechanical behaviour of these hooks. When pulled through the odonotocete lip, the M-16 and M-18 hooks straightened along their entire length, which allowed the hook to bend beyond a 90° angle (Figure 6). The Mustad J-9 hook deformed in a manner similar to that of the M-16 and M-18 hooks. This straightening of the Mustad hook exposed the extremely sharp barb, which sliced through the soft tissue, releasing the hook usually intact. The exit wounds along the lateral lip were either narrow vertical or inverted triangular-shaped lacerations (Figure 7). In contrast, although the proximal bend of the K-16 and K-18 hooks straightened when pulled through soft tissues, the sharp distal portion of the bend did not, thus, leaving the distal "hook" in place (Figures 6 and 8). To fully exit the lip tissue, the Korean hooks either (i) tore through the tissue intact, usually leaving a jagged exit wound or (ii) broke—invariably at the level of the barb—also creating a jagged exit wound and often leaving the barbs embedded in the lip tissue.

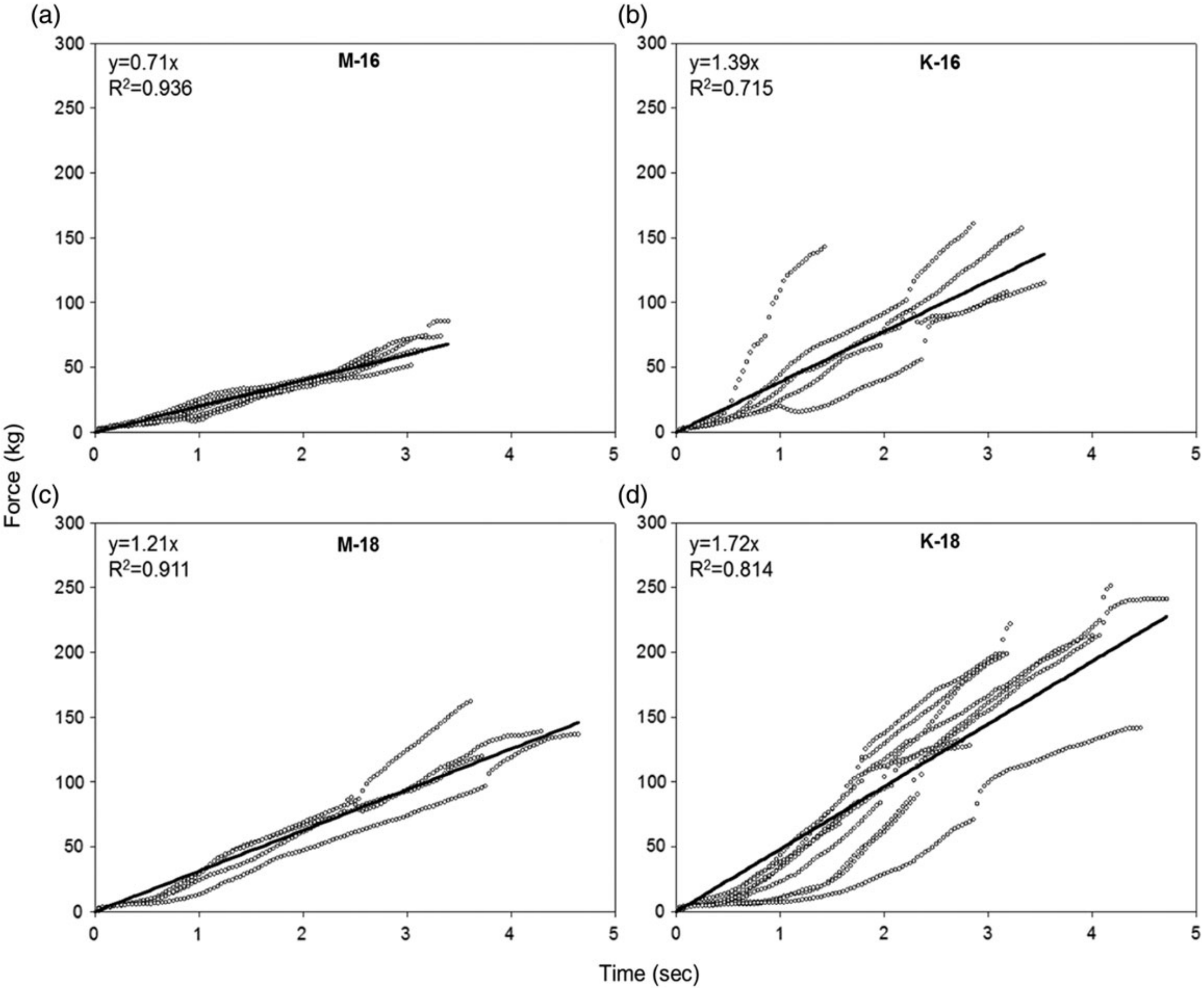

Figure 5. Loading curves for circles hooks tested, including Mustad weak hooks M-16 and M-18 (a and c) and Korean K-16 and K-18 (b and d). Regression line generated from all data points (28 Hz sampling rate) for each test. Time is displayed in the x-axis.

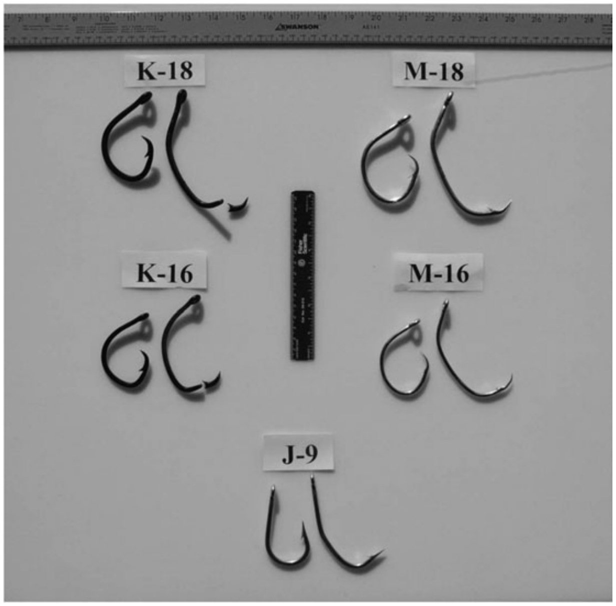

Figure 6. Representative pre- and post-trial forms of hooks utilized in pulling tests. The Mustad 16-0, 18-0, and J-9 hooks straighten along their length and expose the sharp barb. The Korean K-16 and K-18 hooks retain a sharp distal bend and the barbs often break off.

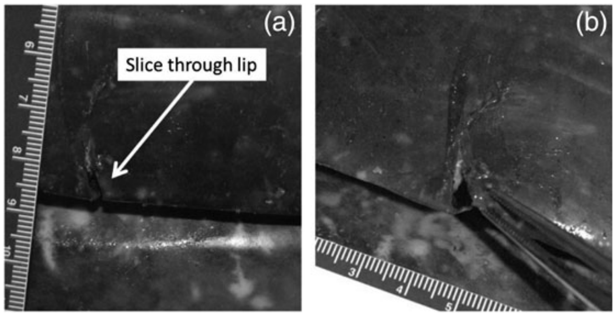

Figure 7. Laceration on the dorsal lip of Risso's dolphin KLC 136 caused by Mustad J-9 hook. (a) Laceration along the lateral margin of the lip and (b) same laceration reflected to reveal the triangular shape of injury.

Longline hook behaviour around the lingual surface of the mandible

The second goal of the study was to determine whether longline hooks could fracture the odontocete mandible. Attempts were made to place all hook types around the mandible, but only two hooks, the M-18 and K-18, had sufficiently wide gapes to allow the hook to encircle the mandible and secure the hook in this position. In all three tests, the hooks produced bone fractures when force was applied.

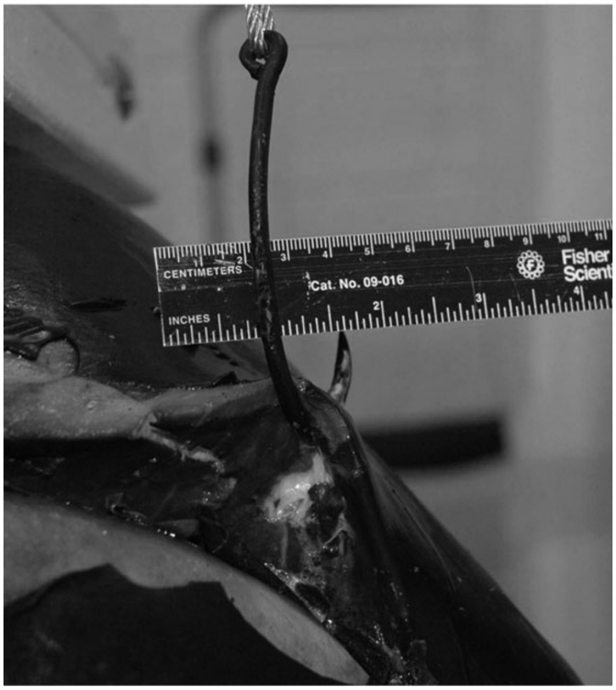

Figure 8. Korean K-18 hook in the dorsal lip of short-finned pilot whale KLC 111. This test was terminated before the force required to pull this hook through the lip was achieved. Note that the hook had torn through the deep lip tissue and if pulled completely out would create a large, irregular wound.

The K-18 hook was first tested in the left mandible of short-finned pilot whale KLC 111, during the first experimental trials of the study. The hook was placed at approximately one-third the length of the lower jaw caudal to the ramus. When pulled, the proximal bend of the hook straightened, but the sharp distal portion of bend of the hook did not. This K-18 sustained a peak force of 141 kg, fractured the bone, and remained embedded in place whole, as the entire apparatus was lifted from the floor, and the experiment was terminated. Subsequent dissection revealed that the hook had embedded on the lingual surface of the mandible, fracturing both medial and ventral portions of the bone in that region (Figure 9).

The second K-18 hook was tested in the right mandible of short-finned pilot whale CAHA 093, at a position in the rostral third of the lower jaw. When pulled, the hook sustained a peak force of 182 kg, the proximal portion of the bend of the hook straightened, and the bone fractured. The hook pulled free, but the distal tip of the hook was broken off. Subsequent dissection revealed that the hook tip and barb punctured into, and had remained deeply embedded in the bone.

The M-18 hook was tested once in the left mandible of Risso's dolphin KLC 136. The hook was positioned at approximately mid-length of the lower jaw. When pulled, this hook sustained a maximum load of 243 kg, fractured the jaw, and then pulled free. It had straightened, as was typical of M-18 hooks in soft tissue, but $\sim$0.5 cm of its distal tip was missing. Subsequent dissection demonstrated that the hook had cleanly separated a large portion of the pan region from the rostral tooth bearing region of the mandible.

Discussion

The present study was, to the best of our knowledge, the first to investigate the behaviour of longline hooks within the mouths of odontocete cetaceans. When pulled through soft tissue of the lip, the behaviour of each hook was strongly dependent upon the material properties of the hook itself. The polished steel Mustad M-16, M-18, and J-9 hooks straightened smoothly along their length, which caused them to open and expose the extremely sharp barbs

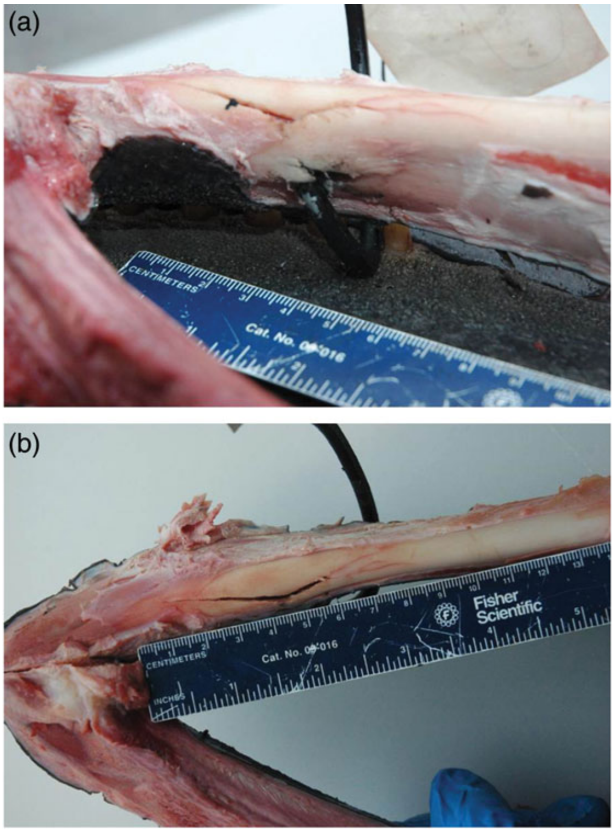

Figure 9. Dissected lower jaw of short-finned pilot whale KLC 111 revealing Korean K-18 longline hook embedded in the left mandible. (a) Ventro-medial view of the left mandible displaying the entry puncture of the hook into lingual surface and compound fracture. (b) Ventral view of the left mandible displaying compound fracture.

(Figure 6). This change in hook shape allowed these hooks to slice through the soft tissue (Figure 7), rather than tear it. The sharp barb, thus, acted like a knife cutting its way out of the cetacean lip. It is not known how these wounds would heal in the wild, but complete wound healing from shallow, experimental lacerations has been documented to occur in the bottlenose dolphin (*Tursiops truncatus*) in as few as 7 d (Bruce-Allen and Geraci, 1985).

The forged carbon Korean K-16 and K-18 hooks behaved much differently from the polished steel Mustad hooks. The Korean hooks were more brittle and fractured more readily than the Mustad hooks. (When tested in isolation, Korean hooks consistently failed catastrophically by fracturing into multiple pieces.) Because the distal, sharp bend of these hooks would not straighten to allow release when pulled, the hooks either tore through lip tissue or broke at the barb and released. Both events produced more irregular, jagged exit wounds and broken barbs were often left embedded in the lip. We hypothesize that these more destructive tissue injuries may take longer to heal than the slices delivered to soft tissue from the M-16, M-18, and J-9 steel hooks.

The exit wounds along the lateral lip caused by longline hook releases in this study, whether lacerations or tissue tears, resemble healed scars observed in stranded short-finned pilot whales (*G. macrorhynchus*), Risso's dolphin (*G. griseus*), and false killer whales (*P. crassidens*; e.g. see Figure 3 and Moore and Barco, 2013).

One additional set of tests was conducted to determine the probability of fracturing the mandible of these odontocetes. Only the M-16 and K-16 hooks were wide and long enough to be placed around the mandible and onto its lingual surface. In all tests of these hooks, the hook was strong enough to fracture the mandible. Oremland *et al.* (2010) described mandibular fractures in 44% of the short-finned pilot whales investigated in their study of museum specimens, and identified interactions with longline fisheries as one of their potential causes. This information supports a determination of serious injury should a hook become entangled in the jaw of a small cetacean (Andersen *et al.*, 2008).

Management considerations

Mechanical testing of biological tissues, and their interactions with fishing gear, can offer insights into how to mitigate the impacts of entanglement (e.g. Winn *et al.*, 2008: Barco *et al.*, 2010). Such insights, though, must be tempered by acknowledging that mechanical tests cannot necessarily model the dynamic and event-specific features of such an entanglement. However, the results of this study suggest important points of consideration for future management decisions.

(i) The material from which the hook is made strongly influences its mechanical behaviour within odontocete cetacean soft tissues. The more ductile, polished steel hook type (Mustad M-16, M-18, J-9) responded to being pulled through lip tissue by straightening along its entire length, thus, opening and exposing the sharp barb at its tip. This change in shape permitted the barb to act like a knife and cut its way through the lip. The resulting injury was usually a linear, clean slice. In contrast, the forged carbon Korean hooks did not open completely, resulting in more irregular, tearing injuries to tissues, and sometimes leaving broken barbs in the soft tissues. The mechanical behaviours of the Mustad weak circle hooks were also more consistent than that of the Korean forged hooks. *Thus, the polished steel Mustad hooks appear to result in less tissue damage, and respond to pulling forces in a more consistent manner, than do the Korean forged hooks.*

(ii) The mechanical behaviours of these hooks were consistent across species tested. Although it is likely that the material properties of the odontocete lip vary slightly along its length, and across species, the results of this study indicate that the hooks behave similarly regardless of these differences. *Thus, it is likely that mechanical behaviours of the hooks tested here provide good models for their behaviours in other, similarly sized odontocetes.*

(iii) The combined gape and bite of the hook make it more or less likely to be able to be hooked onto the deep, lingual surface of the mandible, which can result in fracturing the bone. The M-18 and K-18 hooks could be twisted and fit around the mandible of short-finned pilot whales and Risso's dolphins. When force was exerted upon these hooks, they fractured the bone and either remained embedded or broke, leaving portions of the hook in the jaw. *Thus, hooks with larger gapes and bites, regardless of the material from which they are made, can hook into the jaw and fracture this bone.*

Taken together, the results of this study suggest that hooks formed by ductile polished steel, and of the smallest gape possible to prosecute a fishery, will reduce the potential for serious injury in odontocetes that become hooked after engaging in depredation. These results pertain only to minimizing (i) tissue damage to lip soft tissues and (ii) the potential of a complete hooking of the lower jaw. Further mechanical tests of additional hooks used by industry, and the behaviour of hooks placed in the appendages of odontocetes, should be investigated. Similar biomechanical tests conducted on target species might help focus the size and strength of hooks that are required to retain catch but release marine mammals.

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