Acoustic and stiffness properties of gillnets as they relate to small cetacean bycatch

T. Aran Mooney, Whitlow W. L. Au, Paul E. Nachtigall, and Edward A. Trippel

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Small cetaceans are incidental bycatch in gillnet fisheries. Dolphin and porpoise bycatch has been reduced by the use of barium sulphate-enhanced gillnets. This decreased entanglement is likely the result of either higher acoustic reflectivity or greater stiffness for barium nets. To address these variables, our study quantified the acoustic reflectivity and stiffness of six net types including barium sulphate, iron oxide-enhanced and control demersal gillnets of sizes which typically target cod (*Gadus morhua*) and monkfish (*Lophius americanus*). Acoustic reflectivity, or target strength (TS), was assessed using dolphin and porpoise-like sonar signals from 0° to 40°. TS values were used to calculate likely detection ranges. Barium sulphate- and iron oxide-enhanced nets showed increased reflectivity compared with control nets, with the barium sulphate nets generating the highest TS values. Dolphins should detect these nets in time to avoid contact, but porpoises, with typically lower source levels, may not detect nets at a range great enough to avoid entanglement. Barium sulphate line was significantly stiffer than comparable nylon line. All lines lost stiffness when soaked in seawater for 24 h. Barium sulphate nets proved stiffer and more acoustically reflective, and both factors are likely important in reducing harbour porpoise bycatch.

Keywords: bottlenose dolphin, bycatch, gillnet, harbour porpoise, net stiffness, target strength.

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T. A. Mooney, W. W. L. Au, and P. E. Nachtigall: Department of Zoology, Hawaii Institute of Marine Biology, University of Hawaii, 46-007 Lilipuna Rd, Kaneohe, HI 96734, USA. E. A. Trippel: Fisheries and Oceans Canada, St Andrews Biological Station, St Andrews, New Brunswick, Canada E5B 2L9. Correspondence to T. A. Mooney: tel: +1 808 2475063; fax: +1 808 2475831; e-mail: mooneyt@hawaii.edu

Introduction

There is wide concern that top-level marine predators are increasingly facing human-induced pressures (Pauly *et al.*, 2002; Myers and Worm, 2003). Of particular importance is the reduction of these predator populations by industrial fishing methods, either as targeted or incidental catch. Commercial fishing has removed or reduced species across taxa and geographic regions, resulting in population declines sometimes estimated to exceed 80% (Perrin *et al.*, 1994; Baum *et al.*, 2003; Myers and Worm, 2003). These steep declines in population size are of special concern because the absence of a top predator may have ecological impacts on an entire community (Simenstad *et al.*, 1978; Ripple and Beschta, 2003). Mitigating top predator bycatch, including that of marine mammals, is important to maintain ecosystem stability and fisheries yields (Tegner and Dayton, 1999; Baum *et al.*, 2003).

Both the western North Atlantic bottlenose dolphin (*Tursiops truncatus*) and the harbour porpoise (*Phocoena phocoena*) feed on at least 60 different prey species, including a variety of fish, cephalopods, and crustaceans, many of which are commercially important (Gaskin and Watson, 1985; Recchia and Read, 1989; Fontaine *et al.*, 1994; Gannon and Waples, 2004; Santos *et al.*, 2004). These predators may influence several species and have the potential to project top-down effects on their respective community fauna. Because of their diet overlap with commercially important catch, odontocetes are often found in the same regions as the commercial fisheries (Trippel *et al.*, 1999) and may be at risk of being seriously depleted because of high bycatch in gillnet fisheries.

Tens of thousands of porpoises and dolphins are caught each year worldwide as bycatch (Jefferson and Curry, 1994; Perrin *et al.*, 1994; Read, 2005; Read *et al.*, 2006). Two populations of particular concern in the US are the mid- and North Atlantic harbour porpoise and the mid-Atlantic bottlenose dolphin. The incidental take within these populations has exceeded what the US National Marine Fisheries Service has deemed sustainable in gillnet fisheries, so cetacean-take reduction measures are being implemented (Waring *et al.*, 1999; Cain, 2002).

Bycatch reduction measures vary, but may include reducing fishing seasons or regions (Murray *et al.*, 2000), establishing marine protected areas (MPAs) free of gillnet fishing (Dawson and Slooten, 1993), as well as gear modifications (Dawson, 1991). These measures often differ in effectiveness and consequences. For example, both fishing ground closures and the creation of MPAs could have deleterious social and economic effects on fishing-based communities. However, gear modifications, which are effective at reducing bycatch while maintaining catches of target species, are likely to be popular with both fishers and marine mammal stock managers. Two methods of gear modification related to small cetacean bycatch currently dominate. The first involves the use of acoustic deterrents, or pingers, which emit high frequency sounds intended to alert marine mammals to the presence of fishing gear or drive them from the area. The use of pingers has been correlated with reduced bycatch of harbour porpoises (Kraus *et al.*, 1997; Trippel *et al.*, 1999). However, there are several drawbacks to pingers, including cost, practicality, habituation, variability of success, and a potential "dinner-bell" effect (Dawson *et al.*, 1998; Cox *et al.*, 2001; Trippel *et al.*, 2003).

The second method is the use of an alternative gear type made by modifying nylon gillnets to increase their acoustic reflectivity, so making them easier to detect by echolocating odontocetes. Net alterations tested to date include air-filled nylon line, multifilament nets, weighted filaments woven into nets, and adding a filler (barium sulphate) to the nylon to increase net density (Au and Jones, 1991; Dawson, 1994; Silber *et al.*, 1994; Trippel *et al.*, 2003). Early results of the effectiveness of these modifications varied, with few definitive conclusions. Additional research of modified net material has recently shown more promising results. At some angles, nylon nets enhanced with barium sulphate have proven more acoustically reflective than comparable regular nylon nets (Mooney *et al.*, 2004). Field-tests of these nets have demonstrated reduced bycatch of harbour porpoise (from 2.5% to 0 per set) with maintained catch rates of target fish (Trippel *et al.*, 2003). Precisely why barium sulphate nets reduce porpoise bycatch has yet to be determined (Koschinski *et al.*, 2006). Perhaps in addition to having increased reflectivity, such nets are stiffer than regular nylon nets. Increased stiffness may reduce the tendency of the net to collapse around an animal, thereby reducing chances of entanglement (Larsen *et al.*, 2002; Cox and Read, 2004). Line stiffness has not been formally examined and acoustic reflectivity has only been studied for one type of net material, one line diameter, and one mesh size typically used for cod (*Gadus morhua*). Moreover, net acoustic reflectivity, or target strength (TS), has been measured with simulated broadband dolphin clicks, but not with narrowband porpoise clicks.

We used simulated bottlenose dolphin and harbour porpoise echolocation clicks to compare the TS values of six nets: a barium sulphate net of the size typically used for Atlantic cod, a barium sulphate net of line and mesh size typically used for monkfish (*Lophius americanus*), an iron-oxide-enhanced "cod" net, and three corresponding controls made of traditional monofilament nylon line. Because of its increased density relative to the barium sulphate net, we hypothesized that the iron oxide net would have an even greater acoustic reflectivity. The TS values were measured to estimate distances at which bottlenose dolphins and harbour porpoises would likely detect the various nets under a variety of noise conditions. Finally, the stiffness of barium sulphate and nylon monofilament lines was tested to determine whether barium sulphate nets would be stiffer than regular nylon nets.

Methods

All TS measurements were conducted at the Hawaii Institute of Marine Biology, in Kaneohe Bay, Oahu, Hawaii, in October 2003. To simulate the echoes that an echolocating dolphin or porpoise might hear, biosonar signals similar to those the animals would produce when echolocating were employed. TS values were measured for three experimental net types and three traditional monofilament nylon nets.

The three experimental nets were made of nylon and a filler: (i) a cod net with barium sulphate [$BaSO_4$; 10% by weight, line diameter of 0.60 mm and 147 mm stretched mesh (SM) size], (ii) a larger mesh monkfish net with barium sulphate ($BaSO_4$; 10% by weight, 0.90 mm diameter, SM 305 mm), and (iii) a cod net with iron oxide (Fe_2O_3; 20% by weight, 0.58 mm diameter, SM 152 mm). Fillers were mixed into the liquid nylon by the manufacturer (Atlantic Gillnet Supply, Yardley, PA, USA) before the line was spun. Each of the "filled" nets was compared with a same-sized control nylon net except the iron oxide net. That control net was slightly smaller in line diameter (0.57 mm). The nylon control nets for barium sulphate cod, barium sulphate monkfish, and iron oxide nets are referred to as Controls B, C, and D, respectively. Nets termed "cod" or "monkfish" are nets of the size typically used to catch Atlantic cod or monkfish.

Nets of 9 m^2 area were strung from two 3-m length PVC pipes using ultra-thin 20 lb test (0.457 mm) monofilament line (Figure 1). The top pipe remained out of the water and a sand-filled lower pipe served to weight the net down. The lower PVC pipe rested near the sandy bottom of Kaneohe Bay (5 m depth). Both PVC pipes were out of range of the transducer's beam, and the nets spanned the centre of the transducer's beam. The beam width was 12° and the ensonified area was 0.85 m^2. A monofilament line ran along the sides of the nets from the top PVC pipe to the bottom PVC pipe to resist the tendency of the nets to bow inward in the middle. Thus, nets were hung in such a way so they were not rigid but would move slightly with water as in fishing operations.

Signals were generated by a Qua Tech WSB-10 function board housed in a personal computer, amplified using a Hafler TransNova power amplifier, and transmitted via a custom-built transducer. The transducer utilized a composite piezoelectric circular disc, 0.64-cm thick, manufactured by Material Systems Inc., Littleton, MA, USA. Dolphin-like signals were 80 μs in duration with a peak frequency of 120 kHz and a 3 dB bandwidth of 35 kHz, similar to that of bottlenose dolphins (Figure 2). Porpoise-like signals had a peak frequency of 140 kHz, a 3 dB bandwidth of 15 dB, and were 200 μs in duration. Echoes were collected by a custom-built hydrophone that was separate from the outgoing transducer. The hydrophone had a flat frequency response ($\pm$3 dB) up to 180 kHz. All echoes were gated, amplified, and filtered before being digitized at 1 MHz using a Rapid Systems R1200, and stored on computer. In all, 20 echoes were collected from each target at each position with a 1 s delay between each signal.

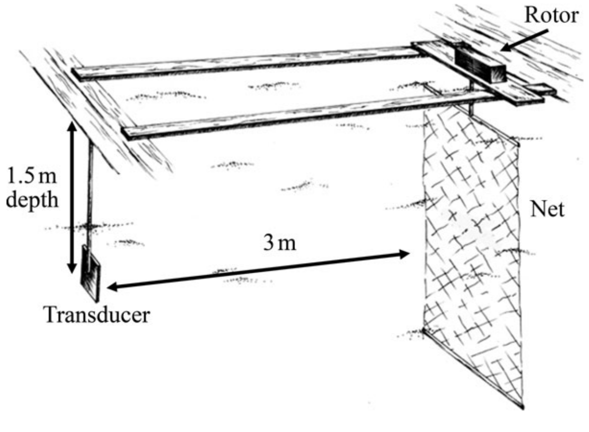

Figure 1. Diagram of the acoustic reflectivity experimental set-up at normal incidence.

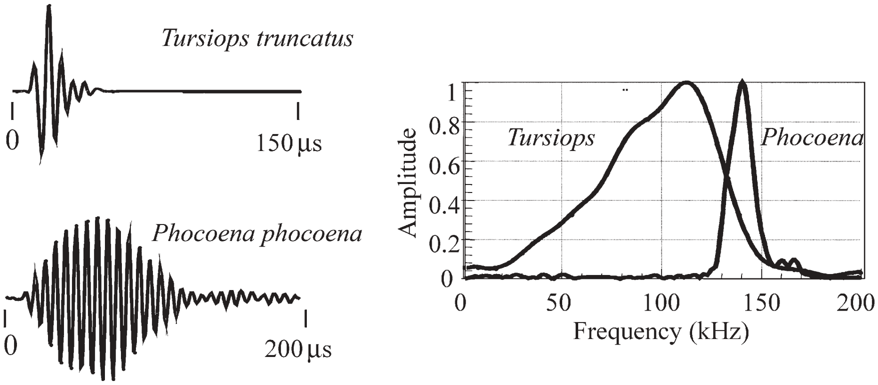

Figure 2. Waveform and spectrum of the broadband dolphin (*Tursiops truncatus*) and porpoise-like (*Phocoena phocoena*) signals that were used to acquire TS measurements of various types of net types.

The transducer was suspended to a depth of 1.5 m, ~3 m from the target. The angle of the net presented to the transducer was varied from normal incidence (0°) to angles of 10°, 20°, 30°, and 40°, where normal incidence was when the plane of the net was perpendicular to the beam of the transducer. Because of relatively high noise levels (NLs) of snapping shrimp (*Synalpheus paraneomeris*), only higher amplitude components of the echoes were readily distinguishable (Au and Banks, 1998). Therefore, peak-to-peak values of the incident and reflected signals were used to determine TS. Peak-to-peak TS can be defined as:

$$\mathrm{TS} = 20\log(p_r/p_i), \tag{1}$$

where p_r is the sound pressure of the target referenced to 1 m from the target, and p_i is the sound pressure of the incident signal at the target.

A total of 20 clicks and the 20 corresponding echoes were recorded for each net at each angle, making 1200 echoes (600 dolphin and 600 porpoise echoes). Despite our best efforts to exclude them, snapping shrimp signals were occasionally recorded within the echo data. Therefore, echoes were assessed qualitatively to remove data where noise was higher than the peak-to-peak echoes of the net. These echoes were not included in our analysis, yielding a total of 1184 echoes. TS was calculated, and respective experimental and control nets were compared.

Statistical analyses were conducted by implementing analysis of variance (ANOVA) with net type and angle of incidence to determine whether differences existed between experimental and control nets. All residuals demonstrated normal distribution of TS values. Because significant differences were found among nets, Tukey's pairwise comparisons assuming unequal variance were employed to determine where the significant differences lay. Both Excel and Minitab software were used for data analyses.

Predictions of biosonar detection ranges were determined from TS measurements. To address the issue of high snapping shrimp noise, we used a noise-limited sonar equation modified for *T. truncatus* expressed in dB (Au, 1988):

$$\mathrm{DT}_E = \mathrm{SL} - 2\mathrm{TL} + \mathrm{TS}_{tt} - (\mathrm{NL} - \mathrm{DI}), \tag{2}$$

where DT is the detection threshold, SL the source level, TL the one-way transmission loss, TS_{tt} the TS based on energy within a bottlenose dolphin's integration time (264 μs), NL the noise level, and DI is the receiving directivity index of the echo.

One-way transmission loss can be expressed in a similar format that provides for the spherical spreading loss, and an absorption term (α) evaluated at the peak frequency of the dolphin sonar signal. For the bottlenose dolphin, we estimated an α of 0.044 dB m^{-1} referenced to 24°C (Kaneohe Bay temperature). The transmission loss for range (R) can be expressed as:

$$\mathrm{TL} = 20\log R + \alpha R. \tag{3}$$

Assuming the same directivity index and detection threshold and inserting the newly calculated SLs, Equation (2) can be rewritten as

$$\begin{aligned} 2\mathrm{TL}_{\mathrm{DL}} &= (\mathrm{SL}_{\mathrm{DL}} - \mathrm{SL}_{\mathrm{KB}}) + (\{\mathrm{TS}_{tt}\}_{\mathrm{DL}} - \{\mathrm{TS}_{tt}\}_{\mathrm{KB}}) \\ &\quad - (\mathrm{NL}_{\mathrm{DL}} - \mathrm{NL}_{\mathrm{KB}}) + 2\mathrm{TL}_{\mathrm{KB}} \end{aligned} \tag{4}$$

to calculate detection range for the bottlenose dolphin and the harbour porpoise. In Equation (4), subscripts DL and KB refer to a different location and Kaneohe Bay, respectively. Predictions of detection ranges were conducted for a wide range of SLs, because bottlenose dolphins and harbour porpoises have the ability to vary the intensity of echolocation clicks (Moore and Pawloski, 1990; Au *et al.*, 1999). NLs were varied from those found in relatively calm, quiet seas to rougher seas to account for different sea states. Assuming deep, open water (>50 m) the noise at 120 kHz is at the thermal limit and equivalent to 27 dB re: 1 μPa when seas are relatively calm (Beaufort sea states 1–3). NLs then increase as sea states increase, to ~33 dB at Beaufort sea state 6 (Urick, 1983).

Equation (4) was solved for the transmission loss in a different location using a value of α of 0.03 dB m^{-1} for deep-water temperatures of 5°C. This value was then substituted in Equation (3) to determine the detection ranges of nets for a bottlenose dolphin and a harbour porpoise in Kaneohe Bay, and in locations where odontocetes are taken as bycatch.

Flexural stiffness (FS) of barium sulphate line and conventional monofilament nylon was quantified following Klust (1973). Stiffness measures were not conducted for iron oxide line because we were unable to procure unwoven line of this material. For flexible items such as fishing line, FS is a descriptor of the overall mechanical behaviour of an object and its deformation under a given load (Etnier, 2001). For each line type, 30 samples were cut, looped, and suspended from a metal clamp such that the loop was 40 cm in circumference and naturally formed a downward teardrop shape. A preweighed cup was hung from the bottom of the loop of line. Water was then added to the cup dropwise using a graduated glass burette to increase the mass of the cup. This increase in mass or downward force decreased the loop diameter. When the loop diameter reached 5 mm distance at its widest point, the mass was noted as a measure of FS. The exact time relative to downward force was recorded by digital video recording and analysed later by three independent observers. Stiffness was tested using dry line and line that had been soaked in seawater for 24 h, a typical gillnet set time in the Bay of Fundy and elsewhere, because properties of line stiffness were thought to change when line was immersed in water. Analyses were calculated using a one-way ANOVA in Minitab software.

Results

Target strengths

In all, 60 measurements of TS are presented based on 1184 individual echoes; approximately 100 echoes for each net minus some echoes which overlapped with snapping shrimp noise. In all cases, there was an inverse relationship with angle of incidence and TS such that as angle of incidence increased, TS decreased. At an angle of 40°, the echo of the net was lost in the background noise of the measurement site.

Dolphin-like clicks

At normal incidence, there was no significant difference between the TS of the barium sulphate and the corresponding control net ($p > 0.05$) (Figure 3). However, as the angle of incidence increased, the barium sulphate net had significantly greater TS values than that of the nylon control, up to 40° when both nets were lost in the background noise ($F_{9,160} = 558.21$; $p < 0.001$). The barium sulphate monkfish net measured significantly higher TS values than its control for all angles except 20° ($F_{9,170} = 61.97$; $p < 0.001$). The iron oxide net had significantly greater TS values than its control at all angles up to 40°. The barium sulphate net exhibited significantly greater TS values than the iron oxide net from 0° to 30° ($F_{9,190} = 165.69$; $p < 0.001$). At 10°, 20°, and 40°, the barium sulphate cod net measured significantly higher in TS than the barium sulphate monkfish net ($F_{9,160} = 130.09$; $p < 0.001$). From 10° to 30°, the dolphin click, when compared with the harbour porpoise click, produced significantly higher TS values for the barium sulphate net ($F_{9,160} = 300.40$; $p < 0.001$).

Predicted detection ranges for bottlenose dolphin

SLs and background NLs were estimated as part of predicted detection ranges in order to simulate several conditions when an

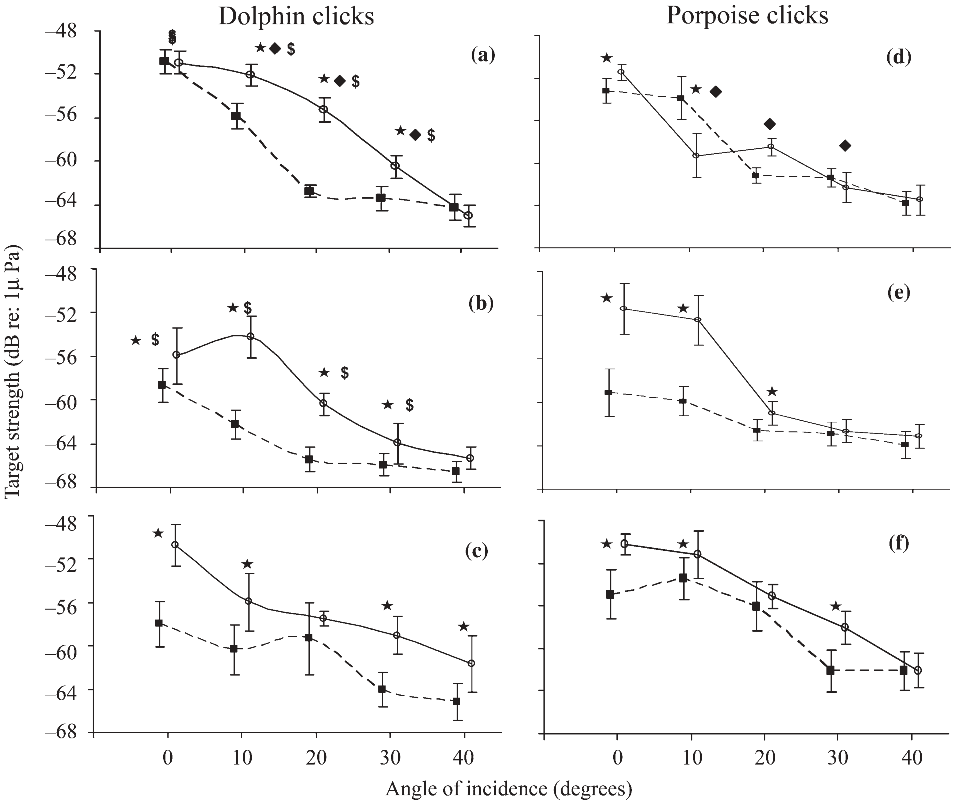

Figure 3. TSs of various nets from angles of 0°–40° using both dolphin (a–c) and porpoise-like clicks (d–f). Experimental nets are indicated using open circles and solid line. Nylon controls for each respective net are represented by black squares and dashed lines, and displayed with the corresponding experimental net. Stars indicate significant differences ($p < 0.05$) between experimental nets and respective controls. Diamonds indicate significant TS differences ($p < 0.05$) using dolphin vs. porpoise clicks for the barium sulphate net. Dollar signs indicate significant TS differences ($p < 0.05$) between barium sulphate and iron oxide nets. (a) $BaSO_4$ and Control B, (b) Fe_2O_3 and Control D, (c) Monkfish $BaSO_4$ and Control C, (d) $BaSO_4$ and Control B, (e) Fe_2O_3 and Control D, and (f) Monkfish $BaSO_4$ and Control C.

Table 1. Predicted detection ranges (m) for a bottlenose dolphin for all nets using SLs of 170–180 dB in 27–33 dB of noise.

NL	SL	Net material	Angle of incidence				
			0°	10°	20°	30°	40°
27 dB	170 dB	$BaSO_4$	10.9	10.2	8.5	6.4	4.9
		Control B	10.9	8.2	5.6	5.4	5.2
		Monkfish	11.0	8.2	7.5	6.9	5.9
		Control C	7.3	6.4	6.8	5.2	4.9
		Fe_2O_3	8.2	9.0	6.4	5.2	4.8
		Control D	7.0	5.8	4.8	4.7	4.5
	180 dB	$BaSO_4$	18.8	17.7	14.8	11.1	8.6
		Control B	18.9	14.3	9.8	9.5	9.0
		Monkfish	19.0	14.3	13.1	12.0	10.4
		Control C	12.8	11.2	11.9	9.1	8.6
		Fe_2O_3	14.3	15.7	11.2	9.2	8.5
		Control D	12.3	10.1	8.4	8.2	7.9
33 dB	170 dB	$BaSO_4$	7.8	7.3	6.1	4.5	3.5
		Control B	7.8	5.9	4.0	3.8	3.6
		Monkfish	7.9	5.8	5.4	4.9	4.2
		Control C	5.2	4.6	4.8	3.7	3.5
		Fe_2O_3	5.9	6.4	4.6	3.7	3.4
		Control D	5.0	4.1	3.4	3.3	3.2
	180 dB	$BaSO_4$	13.5	12.7	10.6	7.9	6.2
		Control B	13.6	10.3	7.0	6.8	6.4
		Monkfish	13.7	10.2	9.4	8.6	7.4
		Control C	9.2	8.0	8.5	6.5	6.1
		Fe_2O_3	10.3	11.3	8.0	6.5	6.1
		Control D	8.8	7.2	6.0	5.8	5.7

Each experimental net is listed above its respective control net.

odontocete might encounter the net. Because an animal might approach the net from any direction, a variety of encounter angles was used in calculations. Predicted detection ranges of the various types of nets by bottlenose dolphins and harbour porpoises are presented and grouped by species into similar SLs and NLs. For 52 of 60 instances, experimental filled nets were predicted to be detected at ranges greater than their respective nylon control net (Table 1). At low SLs and NLs (170 and 27 dB, respectively) and smaller angles (0–30°), the bottlenose dolphin was predicted to detect nearly all nets at a range of >5 m. At NL (40°), four nets, the barium sulphate, control C (monkfish control), the iron oxide, and the control D (iron oxide control) were predicted to be detected at ranges of <5 m. When SLs of 180 dB were used, estimated detection ranges were much higher, generally >10 m for all nets at angles of 0–20°. At this SL, the predicted detection ranges were all >5 m. For SLs of 200 and 210 dB, detection ranges were predicted to be at least 23.8 m (nylon control D, 200 dB, 40°) and up to 50–80 m (Figure 4).

When the NLs were increased to 33 dB, there were considerably more circumstances where the predicted detected ranges were <5 m. Using an SL of 170 dB, only 2 of 15 nets were predicted to be detected at ranges >5 m at 20° and above. In this condition, no net was predicted to be detected at more than 7.9 m. With a 180 dB SL, all nets were predicted to be detected at ranges >5 m. Using SLs of 200 and 210 dB, predicted detection ranges were considerably higher and varied from 17.2 m for control D (iron oxide control) at 40° to 64.6 m for the monkfish net at 0°.

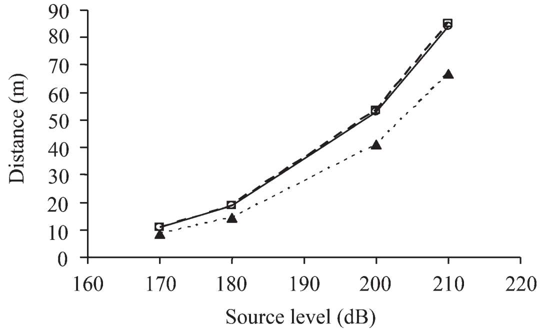

Figure 4. Maximum predicted detection ranges using dolphin-like clicks for the three experimental net types. $BaSO_4$ cod: open circles, solid line; $BaSO_4$ monkfish: open squares, dashed line; iron oxide: black triangles, dotted line.

Porpoise-like clicks

Using a porpoise-like echolocation click, the TS values of the barium sulphate cod net were significantly different from its control net at angles of incidence of 0° and 10° ($F_{9,190} = 229.12$; $p < 0.001$) (Figure 3). From 20° and higher, reflections from both nets appeared lost in the background noise. At most angles, the barium sulphate monkfish net had significantly greater TS values than its control ($F_{9,190} = 162.77$; $p < 0.001$). The iron oxide net had significantly greater TS values than the similar control from 0° to 20° ($F_{9,160} = 96.96$; $p < 0.001$).

Predicted detection ranges for harbour porpoise

Harbour-porpoise-predicted detection ranges followed trends similar to the bottlenose dolphin results, although generally much lower in range. Of 60 calculated detection ranges, 35 were <5 m (as opposed to 24/60 for the dolphin) (Table 2). For lower SLs and NLs (170 and 27 dB, respectively), the detection range of the iron oxide control was predicted to be <5 m at all angles. At an angle of 30°, only the monkfish net was predicted to be detected at a range >5 m. All predicted detection ranges at 40° were <5 m. At SLs of 180 dB and NLs of 27 dB, ranges increased and all predicted detection ranges were >5 m, with 11 of 30 estimates >10 m. Detection ranges with SLs greater than 180 dB were not estimated because porpoises are not known to use clicks with such high intensity in open water environments (Au *et al.*, 1999). When NLs were increased to 33 dB, trends in the predicted detection ranges were quite similar to 27 dB of noise (Table 2).

Flexural stiffness

A strong positive relationship was found between line diameter and line stiffness of the control nylon line, so as diameter increased, so did line stiffness (r^2 value $= 0.925$, $p < 0.001$, $y = 903.808x - 277.511$, $n = 180$). A significant difference in FS was found between all samples except between the 40 lb test nylon and the barium sulphate line (one-way ANOVA; $F_{6,203} = 1617.6$; $p < 0.001$) (Figure 5a). However, barium sulphate line was considerably smaller in diameter than the 40 lb test line (40 lb, 0.59 mm; $BaSO_4$, 0.51 mm). The breaking strength of barium sulphate line was also estimated (by the manufacturer) to be less than

Table 2. Predicted detection ranges (m) for a harbour porpoise for all nets using SLs of 170–180 dB in 27–33 dB of noise.

NL	SL	Net material	Angle of incidence				
			0°	10°	20°	30°	40°
27 dB	170 dB	$BaSO_4$	7.5	4.8	5.4	4.1	3.8
		Control B	6.8	6.6	4.4	4.3	3.8
		Monkfish	8.0	7.6	6.1	5.2	4.1
		Control C	6.2	6.7	5.8	4.1	4.1
		Fe_2O_3	7.5	7.1	4.4	4.0	3.9
		Control D	4.9	4.7	4.0	3.9	3.7
	180 dB	$BaSO_4$	13.2	8.5	8.9	7.2	6.7
		Control B	11.9	11.5	7.6	7.6	6.6
		Monkfish	14	13.3	10.7	9.1	7.3
		Control C	10.8	11.1	10.2	7.3	7.3
		Fe_2O_3	13.2	12.5	7.7	7.0	6.9
		Control D	8.6	8.2	7.1	6.9	6.5
33 dB	170 dB	$BaSO_4$	7.5	4.8	5.1	4.1	3.8
		Control B	6.8	6.6	4.3	4.3	3.8
		Monkfish	8.0	7.6	6.1	5.2	4.1
		Control C	6.2	6.7	5.8	4.1	4.1
		Fe_2O_3	7.5	7.1	4.4	4.0	3.9
		Control D	5.2	4.7	4.0	3.9	3.7
	180 dB	$BaSO_4$	13.1	8.5	8.9	7.2	7.1
		Control B	11.9	11.5	7.6	7.6	6.6
		Monkfish	14	13.3	10.7	9.1	7.3
		Control C	10.8	11.7	10.2	7.3	7.3
		Fe_2O_3	13.2	12.5	7.7	7.0	6.9
		Control D	8.5	8.2	7.1	6.9	6.6

Each experimental net is listed above its respective control net.

equivalent diameter nylon line with a 28.5 lb rating. Barium sulphate line was significantly stiffer than 30 lb test nylon line of the same diameter (30 lb, 0.51 mm).

The stiffness of line that was soaked in seawater for 24 h was compared with the stiffness of dry line (Figure 5b). For all three line types tested, 40 lb, 30 lb, and experimental barium sulphate, there were significant differences between dry and soaked line samples ($n = 60$; $F_{5,174} = 719.68$; $p < 0.001$). Logically, the line soaked in seawater for 24 h was significantly more flexible than dry line.

Discussion

The results demonstrated that nets woven of barium sulphate- or iron-oxide-enhanced line are generally more acoustically reflective than comparable nylon nets. The differences in TS were found at or near perpendicular angles. Of the 12 measurements at 0° and 10°, 11 exhibited significant differences between experimental and control nets. At bigger angles, echo strength relative to NLs was extremely low, and often at 40°, no echo was recorded at all. Therefore, echolocation detection ranges would likely be lower than reported here with incidence approach angles of 40° and above. Following these data, if one assumes that range decreases linearly with increasing angle of incidence, a linear regression could be calculated for barium sulphate and control B net detection ranges using angles 0°–30°, where echoes are presumably detectable (Figure 6). These types of data from the two net types were pooled because regression lines were extremely close. The subsequent regression line was then extrapolated for larger angles ($r^2 = 0.78$; $p < 0.01$; $y = -0.0965x + 6.935$; $n = 8$). In this extrapolation, the hypothetical animals' detection range declined to <3 m at angles of 40° and above. Although one cannot extrapolate more accurately the decrease in detection range at greater incidence angles, it is clear that the direction from which an animal approaches the net plays an important role in whether or not it detects the net. This finding greatly reduces the practicality of developing an "acoustically enhanced" net.

Net TSs decreased at bigger angles of incidence because echo duration increased with angle of incidence. Nets are not actually one single target but are made up of many small targets, or acoustic scatterers, e.g. the lines and knots. At normal incidence, the clicks reflect off the relatively perpendicular face of the net simultaneously. As the angle of incidence increases, the various scatterers that make up the net echoes are rotated, resulting in different distances from the transducer (or echolocator). This results in the echo returning to the receiver from different portions of the net at different times, decreasing the signal-to-noise ratio and lowering the net-detection ranges.

The estimated detection ranges also decreased considerably with lower intensities of the simulated echolocation signals. This result is particularly important for harbour porpoises which tend to echolocate at lower SLs than bottlenose dolphins even in open water (Au, 1993; Au *et al.*, 1999; Koschinski *et al.*, 2006). Consequently, porpoises may not detect the nets until they are at a relatively close range, and may have a more difficult time detecting any net (Mooney *et al.*, 2004). Most nets might be detected at reasonable distance if the animal approaches perpendicular to the net (Figure 4). However, if the animal approaches from greater angles of incidence (>40°), or when it is not echolocating or is echolocating quietly, the net will likely not be detected. Additionally, in environments with high NLs, such as shipping zones, demersal areas, or in rough, shallow seas, net detection may be further impeded.

Comparing the net TSs, the barium sulphate and control net reflectivities were similar to previous tests in that significant differences occurred at 10–30° but not at 0° or 40° (Figure 3; Mooney *et al.*, 2004). Interestingly, the greater line diameter of the experimental monkfish net did not increase its reflectivity over that of the barium sulphate cod net, although the monkfish net line was 67% larger in diameter (knots were also larger in diameter). This was not expected because a net of greater line and knot diameter was anticipated to have greater TS values. The difference in TS values between the two nets was likely attributable to the amount of net mesh within the beam of the transducer. The monkfish net had twice the SM size, or eye size, of the cod net. The larger mesh would have less effective surface area to reflect the acoustic signals, so resulting in lower TS values.

It was also unexpected that despite the higher density, iron oxide nets would have less TS than the barium sulphate nets (Figure 3). The difference may lie in the properties of the added material. Barium sulphate is used in the medical industry as a non-toxic, highly radiopaque material (Tanomkiat and Galassi, 2000). This reflective property may transfer well to acoustic reflectivity. Further, some barium products are piezoelectric, playing particularly enhanced acoustically reflective roles (Park *et al.*, 1999). Barium sulphate may well have piezoelectric properties,

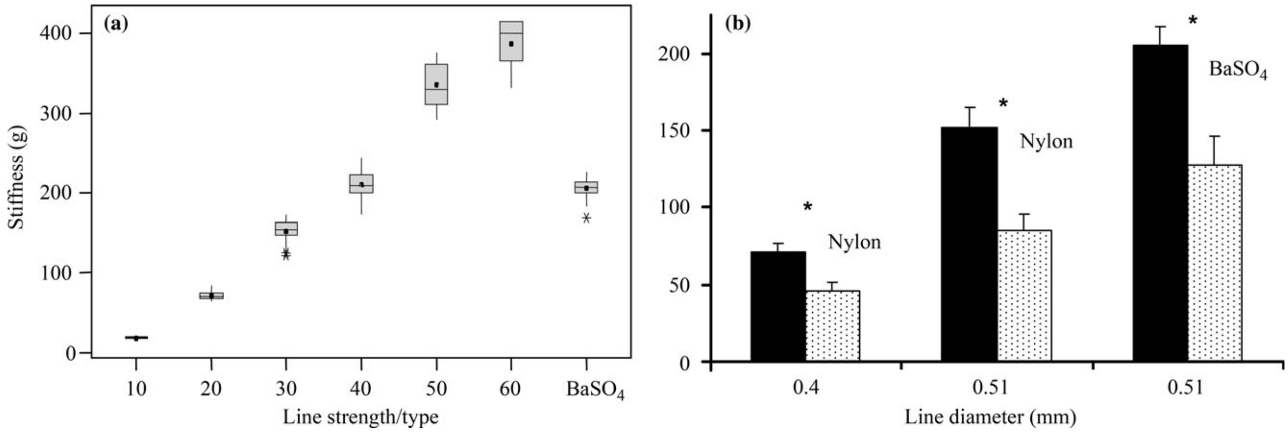

Figure 5. (a) Stiffness of control nylon of various breaking strengths (label in lb test) and experimental barium sulphate line. The dot indicates the mean, grey box indicates median and 2nd and 3rd quartiles, and vertical lines indicate standard deviations. Asterisks indicate outlier points. Significant differences were found between all line types except 40 lb test and barium sulphate line ($p < 0.001$). (b) Stiffness of dry (black bars) and wet (dotted bars) nylon and barium sulphate line. Significant differences (asterisks) were found within all line types between the wet and dry line ($n = 60$; $p < 0.001$).

so the net may reflect better than an iron oxide net of greater density.

The acoustic reflectivities of these nets, up to −50 dB, can be considered reasonably high especially near normal incidence. For perspective, herring (*Clupea pallasi*) TS values measured using a frequency of 120 kHz, the same as this study's dolphin peak frequency, ranged from approximately −32 to −44 dB (Thomas *et al.*, 2002). In the same study, juvenile sand lance (*Ammodytes hexapterus*) had TSs from −67 to −52 dB. The TSs of the nets were within the range of TS values of these fish, both of which serve as prey species for porpoises and dolphins (Fontaine *et al.*, 1994; Gannon and Waples, 2004). The TS of the sand lance, lengths of which varied from 6.2 to 9.8 cm, overlaps the TS of the nets and represents a relatively small reflective target. Therefore, the whole ensonified area of these nets reflects about as much energy as a 7 cm fish or a target small enough to miss or not detect depending on the state of the animal. A larger reflector, such as herring, could mask the echoes of the net.

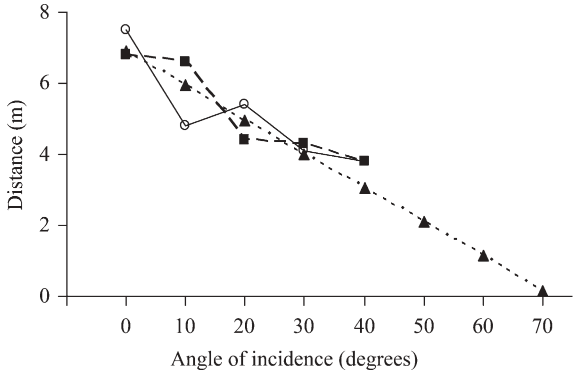

Figure 6. Predicted distance of detection of both barium sulphate and Control B nets by a harbour porpoise based on various angles of incidence at a SL of 170 and NL of 27 dB. A regression line was determined based on all points from 0° to 30° before net echoes were lost in background noise to predict detection at greater angles of incidence ($r^2 = 0.78$; $p < 0.01$; $y = -0.0965x + 6.935$; $n = 8$). $BaSO_4$: open circle, solid line; Control B: black square, dashed line; Regression: black triangles, dotted line).

The predicted detection ranges were generally compared with a range of 5 m, i.e. if the echolocating animal detected the net at a range greater or less than 5 m. The average travel speeds of a bottlenose dolphin range between 2.7 and 5.5 m s^{-1} (Lockyer and Morris, 1987). When swimming at an average speed, detections at >5 m would provide <1 s to avoid the net and might increase the chance of contacting the net. Detection range predictions indicate that the harbour porpoise may often detect the nets at a range <5 m. This would provide very little time for an animal to avoid the net. With its greater SLs, a bottlenose dolphin would likely not contact the net. In fact, an animal emitting high-intensity echolocation clicks may be able to detect these nets at distances upwards of 20 m and perhaps as far as 80 m (Figure 4). Detection ranges would be expected to increase for all animals when the ropes, weights, and floats of the nets are also considered, because these are likely to be better acoustic reflectors than the nylon nets alone (Au and Jones, 1991).

In light of these predictions of detection, it seems that bottlenose dolphins should be able to detect all nets that we examined from a variety of angles. Therefore, one wonders why they become entangled. We summarize three possibilities for this. One is perception. They do not perceive the net as an impenetrable and dangerous object and swim into it (Au and Jones, 1991). A second possibility is detection. The dolphins should be able to detect the net alone, but if the animals are not echolocating or strong echoes of fish targets mask the weak echoes of the net, the dolphin could encounter and become entangled in the net (Au and Jones, 1991). A third possibility is that the dolphin both perceives and detects the net and simply makes a mistake and becomes entangled (Kastelein *et al.*, 1995). This could occur when the animal is taking fish from the net or is paying more attention to foraging or socializing and simply swims into the net (Cox *et al.*, 2003). For porpoises, it may be any or all three reasons for entanglement, but detection of the net itself becomes a significantly greater issue. This notion was supported by Cox and Read (2004), who found on the basis of click trains that it was likely that porpoise detection of acoustically reflective nets was not increased relative to control nets, although the specific behaviours around the nets were not reported.

The stiffness of the nets may have been important because detection ranges for porpoises were considerably shorter, often <5 m, and detection by echolocation at approach angles of $\geq 40^\circ$ may be quite limited. Barium sulphate line was significantly stiffer than similar control nylon line, but if line stiffness is simply the factor in reducing bycatch, as suggested by Cox and Read (2004), bycatch might be reduced using larger diameter, or stiffer, nylon line. However, this might also reduce fish catches, although this has not been shown (Trippel *et al.*, 2003; Cox and Read, 2004). Moreover, all line tested became more flexible after it was soaked in seawater for 24 h. As nets become more flexible animals can become entangled more easily. Longer set times increase the rate of fisheries target and bycatch (Melvin *et al.*, 1999). It has been assumed that increased catch is related to greater exposure time to gear, but it may also be partly due to increased flexibility of the net. Increasing net stiffness might be useful if stiffer nets result in less bycatch.

Although our methods provide a means of quantifying stiffness, the implementation and practical aspects, such as fishing ability, durability, ease of handling, and relative cost, should be assessed. To address these concerns, we recommend that barium sulphate nets be field-tested under a variety of fishing conditions to assess their relative merits, from a number of perspectives, compared with regular nylon nets or those outfitted with acoustic pingers.

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