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Target Strength of a Nylon Monofilament and an Acoustically Enhanced Gillnet: Predictions of Biosonar Detection Ranges

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Abstract

Thousands of marine mammals die each year in fisheries-related entanglements. A substantial number of these animals entangle themselves in gillnets. Two populations in immediate danger are the coastal stock of the mid-Atlantic bottlenose dolphin, *Tursiops truncatus*, and the Gulf of Maine harbour porpoise, *Phocoena phocoena*. We investigated the efficacy of using an alternative net material made with barium sulphate hypothesized to be acoustically more reflective than traditional nets. By using simulated dolphin echolocation clicks, the target strength of the experimental net was compared with the target strength of a similar gauge nylon net. Results demonstrated that at angles greater than normal incidence, but less than 40°, the new barium sulphate net was acoustically more reflective than the nylon net; however, there was no significant difference in the target strength of the two nets at 0°. At angles greater than 40°, both nets were difficult to discern from background noise. Target strengths of the nets were used to calculate detection ranges for *T. truncatus* and *P. phocoena*. Both species should be able to detect the experimental nets at a distance greater than the nylon nets. For *T. truncatus*, this distance may be enough to reduce entanglement; however, because of *P. phocoena*'s lower source level echolocation signals, they may not detect either net with echolocation in time to avoid contact.

Key Words: entanglement, gillnet, take reduction, *Tursiops truncatus*, *Phocoena phocoena*, target strength, acoustic reflectivity

Introduction

The bycatch of marine mammals by fisheries is a problem resulting in threatened or endangered populations and species of cetaceans around the globe. Of particular interest are small echolocating odontocetes, which often entangle and drown in nets, particularly gillnets (Waring et al., 1999). In the USA, the incidental take and mortality of the coastal mid-Atlantic bottlenose dolphin, *Tursiops truncatus*, and Gulf of Maine harbour porpoise, *Phocoena phocoena*, have been identified by the National Marine Fisheries Service (NMFS) as exceedingly high. The bycatches of these two populations by bottom-set gillnet fisheries are greater than what is deemed sustainable to the populations (Cain, 2002; Waring et al., 1999). Several measures have been tested, with variable success, in attempts to reduce the gillnet bycatch of the bottlenose dolphin and the harbour porpoise.

Reducing bycatch of odontocetes in gillnets is a particularly challenging problem because of the properties of the nets, and how they are set increases target catch along with dolphin entanglements. The nets often are set in waters of poor visibility or at depth, where light levels are low (Kastelein et al., 2000). Thus, animals may not be able to detect nets with their vision. Additionally, gillnets are constructed of nylon monofilament, which traditionally has a weak target strength; therefore, regular gillnets reflect sounds, such as echolocation clicks, poorly, and echoes may be difficult to perceive by odontocetes. It is possible that echolocating cetaceans, in particular, will not perceive gillnets as an obstacle because the echoes from the nets are relatively weak (Au & Jones, 1991).

Previous research on reducing porpoise and dolphin bycatch has had variable success (Cox et al., 2001; Gearin et al., 2000; Kraus et al., 1997; Trippel et al., 1999). Because herring catch and harbour porpoise bycatch peaks coincide temporally (Trippel et al., 1996), fishing ground closures might reduce bycatch; however, these closures will have deleterious social and economic impacts on local fisheries. Acoustic alarms, or pingers, appear to reduce harbour porpoise mortality (Kraus et al., 1997), but many concerns exist regarding their long-term effectiveness. Potential drawbacks include cost, practicality, and variability in success of reducing bycatch (Dawson

et al., 1998). Furthermore cetaceans may become habituated to the alarm sound, thus resulting in an ineffective product (Cox et al., 2001).

A third solution to reducing dolphin and porpoise bycatch may be the use of an alternative type of gear. We examined the acoustic properties of a gillnet that has been hypothesized to have an enhanced acoustic reflectivity compared to traditional nylon gillnets. This experimental net, made of nylon with a barium sulphate filler (3% by volume; 10% by weight), is believed to have an increased target strength compared to a regular nylon net. Although acoustic reflectivity was addressed by Trippel et al. (2003), reflectivity to dolphin echolocation signals was not. Additionally, the distance at which the bottlenose dolphin and harbour porpoise may detect the net has not been estimated. The aims of this study were to determine, using simulated dolphin echolocation clicks, whether or not the barium sulphate net has increased target strength, and to predict at what distances an echolocating animal might detect this net.

Materials and Methods

Two types of nets were measured: (1) a traditional nylon net (control net) and (2) a new type of net made with a barium sulphate filler (experimental net). Both nets were 9 m^2, with a twine size of 0.51 mm diameter and a stretched-mesh size of 147 mm. Nets were strung from two 3-m length PVC pipes using ultra-thin 20-lb test (0.457 mm) monofilament line. A top pipe remained out of the water, and a sand-filled lower pipe weighted the net towards the bottom. This lower PVC rested near the sandy bottom of Kaneohe Bay (5 m depth). Both PVC pipes were out of the transducer's beam, and the nets spanned the center of the transducer's beam. The monofilament line also ran along the sides of both nets from the top PVC pipe to the bottom PVC pipe to resist the tendency of both nets to bow inward in the middle. Thus, nets were hung so they were not rigid, but slightly flowed with water as is the case in fishing situations.

Target strength measurements were obtained at the Hawaii Institute of Marine Biology in Kaneohe Bay, Oahu, Hawaii, using a broadband dolphin-like echolocation signal. Signals were generated by a Qua Tech WSB-10 function board housed in a personal computer, amplified using a Hafler P3000 power amplifier, and transmitted via a custom-built transducer. The transducer utilized a 1-3 composite piezoelectric circular disc, 0.64 cm thick, manufactured by Material Systems, Inc., Littleton, Massachusetts, USA. Signals were each 80 μs in duration, with a peak frequency of 120 kHz and a 3 dB bandwidth of 35 kHz. The echo was received by a custom-built hydrophone in the transducer housing and could appropriately be collected and directed by a transmit/receive switch in the housing. Echoes were gated, amplified, and filtered before being digitized at 1 MHz using a Rapid Systems R1200 and stored on the PC. Ten echoes were collected from each target at each position with a 1-s delay between each signal.

The transducer was suspended to a depth of 1.5 m, approximately 3 m from the target. At normal incidence, the plane of the net was perpendicular to the transducer beam. The angle of the net presented to the transducer was varied from normal incidence to angles of 10°, 20°, 30°, and 40° degrees. Due to the relatively high noise levels of the snapping shrimp native to Kaneohe Bay, only higher amplitude components of the echoes were readily distinguishable. Thus, peak-to-peak values of the incident and reflected sound pressure levels were used to determine target strength. Peak-to-peak target strength (TS) is defined by equation (1):

$$TS = 20 \log (P_r/P_i) \quad (1)$$

where, P_r is the sound pressure level of the target referenced to 1 m from the target, and P_i is the sound pressure level of the incident signal at the target.

We compared peak-to-peak TS of echoes from the barium sulphate net vs. that of the nylon net using paired dependent *t*-tests for each angle.

From TS measurements, we predicted biosonar detection ranges. A major concern in this derivation was the biotic noise level of snapping shrimp in Kaneohe Bay. To address the issue of high biotic noise, we used a noise-limited sonar equation modified for *T. truncatus* expressed in dB and derived by Au (1988):

$$DT_E = SE - 2TL + TS_{tt} - (NL - DI) \quad (2)$$

where, DT_E is the detection threshold, SE is the source energy flux, TL is the one-way transmission loss, TS_{tt} is the target strength based on energy within a bottlenose dolphin's integration time (264 μs), NL is 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 referenced to 24 °C (Kaneohe Bay water temperature). The following equation (Au, 1993) also incorporates range of detection (R):

$$TL = 20 \log R + \alpha R \quad (3)$$

Because we used peak-to-peak sound pressure levels for this equation, we used Au's (1988) equation that described the relationship between the SE density and sound pressure levels. This equation provided the SE in equation (2), which

then relates to source levels. Assuming the same DI and DT_E, and inserting the newly calculated source levels, equation (2) can be rewritten as follows:

$$2\,TL_{DL} = (SL_{DL} - SL_{KB}) + (\{TS_{tt}\}_{DL} - \{TS_{tt}\}_{KB}) - (NL_{DL} - NL_{KB}) + 2\,TL_{KB} \quad (4)$$

This equation is used to calculate detection range for the bottlenose dolphin. In equation (4), SL refers to source level and subscripts DL and KB refer to a different location and Kaneohe Bay, respectively. Because bottlenose dolphins have the ability to vary intensity of echolocation clicks (Moore & Pawloski, 1990), predictions of detection ranges for bottlenose dolphins were conducted for a wide range of source levels. The noise level in a different location was varied from relatively calm, quiet seas (27 dB) to rougher seas (33 dB) to account for different sea states. Twenty-seven dB of noise is roughly the ambient noise in Beaufort sea states 1-3, which is before white caps appear on the water. Thirty-three dB is the ambient noise of Beaufort sea states > 4, when white caps are visible.

Equation (4) is solved for the transmission loss in a different location using an α of 0.03 dB/m for deep water temperatures of 5 °C. This value was inserted into equation (3) to determine detection ranges of both nets for a bottlenose dolphin in Kaneohe Bay and in locations where take reduction needs to be implemented.

P. phocoena predictions employed a slightly different method because the harbour porpoise's echolocation click peak frequencies are characteristically around 130 kHz, and ambient noise in this porpoise's environment is typically much lower (Kastelein et al., 1999). Further, target detection experiments have not been published on the harbour porpoise in a noisy environment. Thus, we only applied harbour porpoise predictions to a quiet environment using a simple estimate of two-way transmission loss incorporated into the following equation:

$$TL = 40 \log R + 2\alpha R \quad (5)$$

Additionally, we used an α of 0.038 dB/m based on the peak frequency of 130 kHz and ambient water temperatures of 15 °C.

Previous research (Kastelein et al., 1999) showed that for a 5.08-cm diameter stainless-steel sphere, the 50% correct detection threshold for harbour porpoises was 15.9 m and the 90% correct detection threshold was 12.0 m. The TS of this sphere was measured at -36.6 dB re: 1μPa. Inserting these values into equation (3), we determined the transmission loss that would occur as a harbour porpoise is echolocating on the sphere. Then, TL was determined to be 49.3 dB when the range was 16 m and 44.1 dB when the range was 12 m.

The difference in TS between the nets and sphere can be added to transmission loss to resolve the transmission loss that would occur when *P. phocoena* echolocates on a net. With transmission loss, equation (3) can then be solved for the range of detection for a regular monofilament nylon net or barium sulphate net. Range calculations were determined for each net at the respective angles measured. Additionally, because detection range distances have been established for the 5.08-cm diameter target at both 50% and 90% correct detection levels, we predicted harbour porpoise 50% and 90% detection distances for both nets.

Results

Target Strength Results

At normal incidence, there was no significant difference in target strength between the two nets ($p > 0.05$). Mean TS of the nylon net was -52.7 dB re: 1μPa (n = 20; SD = 1.1) and mean TS of the barium sulphate net was -53.1 dB (n = 20; SD = 2.1) (Figure 1). When the angle of incidence increased to 10°, 20°, and 30°, there was a significant difference (Table 1) between the mean TS of the two nets, regardless of angle ($p < 0.001$). At an angle of 40°, there was no significant difference in TS between the two nets ($p > 0.05$). The mean TS of the nylon net was -61.9 dB (n = 20; SD = 5.7) and the TS of the barium sulphate net was -61.1 dB (n = 20; SD = 6.1). Beyond 40°, both nets had little to no discernable echo relative to the background noise measured in Kaneohe Bay.

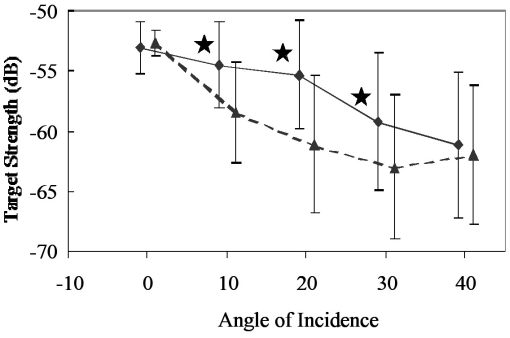

Figure 1. Target strength in dB re: 1μPa of barium sulphate and nylon nets; solid line: barium sulphate net; dashed line: nylon net. Error bars represent standard deviations of the mean for TS measurements. Statistically significant results are marked with a star.

Table 1. Mean target strengths of experimental and control nets; data in dB re: 1μPa. Y: $p < 0.05$; N: $p \geq 0.05$

Angle of incidence	Barium sulphate net	Nylon net	Significant difference
0°	-53.1 ± 2.1	-52.7 ± 1.1	N
10°	-54.5 ± 3.6	-58.5 ± 4.2	Y
20°	-55.3 ± 4.5	-61.1 ± 5.7	Y
30°	-59.2 ± 5.7	-63.0 ± 6.0	Y
40°	-61.1 ± 6.1	-61.9 ± 5.7	N

Phocoena phocoena

We predicted very little difference in detection range of the two nets at 0° from normal (Table 2). At 50% detection rates, maximum detection range of the experimental barium sulphate net was 6.6 m whereas it was 6.8 m for the nylon net detection range. The maximum range of detection is substantially less at 90% detection; for the barium sulphate net, the estimated detection range was 4.9 m and the regular nylon was 5.0 m.

Table 2. Predicted gillnet detection distances (m) by *Phocoena phocoena* for both barium sulphate (BS) and nylon (N) nets at varying degrees of predicted detection

Angle of incidence	Percent correct 90% BS	90% N	50% BS	50% N
0°	4.9	5.0	6.6	6.8
10°	4.5	3.6	6.1	4.9
20°	4.3	3.1	5.8	4.2
30°	3.4	2.8	4.7	3.8
40°	3.1	2.9	4.2	4.0

As the angle of incidence increased to 10°, 20°, and 30°, the predicted detection ranges of the barium sulphate net were considerably greater than the nylon net.

The predicted detection range of both nets was similar at 40° from normal incidence. At 90% probable detection, ranges were as low as 3.1 m for the barium sulphate net and 2.9 m for the nylon net. Predicted detection ranges were slightly higher at the 50% detection probability: 4.2 m for the barium sulphate net and 4.0 m for the nylon net.

Tursiops truncatus

To predict detection ranges for the bottlenose dolphin, both source and noise level were varied. Source level was varied because bottlenose dolphins have the ability to produce clicks over a range of intensities (Moore & Pawloski, 1990), and the source levels used predominantly in the wild have not been established. We used two different noise levels to compensate for varying environmental noise conditions.

At normal incidence, the maximum estimated detection range for a bottlenose dolphin was 77.8 m for the nylon net and 76.4 m for the barium sulphate net, calculated with a source level of 210 dB and noise level of 27 dB (Table 3). Although the difference in predicted detection range is relatively small, the barium sulphate net maintained a greater predicted detection range compared to the nylon net when the angle of incidence was increased to 10°, 20°, and 30°.

Minimum estimated detection range for both nets was at the lowest source level (170 dB), greatest noise level (33 dB), and 40° off normal. At this distance, we predicted the barium sulphate net would be detected at 4.4 m and the nylon net at a similar 4.2 m (Figure 2).

Table 3. Predicted detection distances (M) of gillnets by *Tursiops truncatus* for both barium sulphate and nylon nets; dB re: 1μPa; BS: barium sulphate net; N: nylon net

Source level	Noise level	Net material	Angle of incidence 0°	10°	20°	30°	40°
170 dB	27 dB	BS	9.6	9.4	8.5	6.8	6.1
		N	9.8	7.5	6.2	5.5	5.8
	33 dB	BS	6.9	6.3	6.1	4.9	4.4
		N	7.0	5.1	4.4	3.9	4.2
180 dB	27 dB	BS	16.7	15.5	14.8	11.9	10.7
		N	17.1	12.4	10.8	9.5	9.7
	33 dB	BS	12.0	11.1	10.6	8.5	7.7
		N	12.3	8.9	7.7	6.9	7.3
200 dB	27 dB	BS	47.6	46.5	44.5	34.8	31.5
		N	48.4	36.2	31.7	28.7	30.2
	33 dB	BS	35.2	32.5	31.3	25.4	23
		N	35.8	26.5	23.1	20.9	22.1
210 dB	27 dB	BS	76.4	71.5	68.8	57.4	52.2
		N	77.8	59.5	52.4	47.8	47.9
	33 dB	BS	57.8	56.5	51.8	42.6	38.7
		N	58.8	44.4	38.9	35.3	37.2

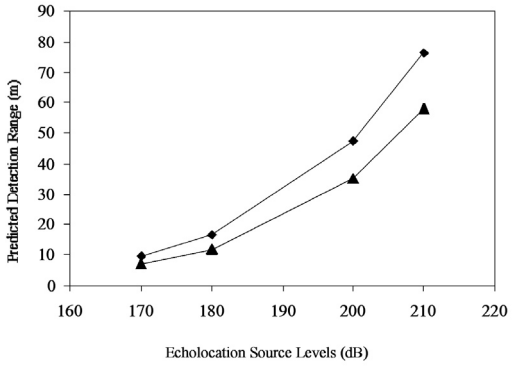

Figure 2. Predicted maximum detection range of a barium sulphate net at normal incidence at increasing source levels (dB re: 1μPa) by *Tursiops truncatus*; diamonds: 27dB of noise; triangles: 33 dB of noise

Discussion

At angles greater than the normal incidence, the barium sulphate net had an increased target strength compared to the nylon net. Thus, it appears that the barium sulphate nets do reflect dolphin echolocation signals better than regular monofilament nets. Both nets had relatively weak target strengths from dolphin-like clicks, however, even at 0°, when reflected acoustic energy was the greatest. Additionally, at 0° there was no significant difference in TS between the two nets and the predicted detection distance. At angles ≥ 40°, the TS of both nets was essentially the same as the background noise and, thus, probably difficult for a dolphin to perceive. We predicted that the barium sulphate net should be detected at a greater range by bottlenose dolphins and harbour porpoises when the net is approached from angles greater than 0°, but less than 40°. At 0°, both nets reflected the same amount of energy and would be detected at the same range. Levels of echolocation-like signals reflected from either net at angles ≥ 40° were not greater than the background noise, at least in our experimental situation, and potentially in other high noise environments.

In this study, source levels were varied for bottlenose dolphins because the amplitude of signals produced by wild animals in the area of the nets is unknown. For the harbour porpoise, which produces lower source levels, we predicted they will only detect nets at a relatively close distance. Maximum detection distance is predicted to be about 10 m. In noisy seas, detection distance may be considerably less. Harbour porpoises swim at speeds up to 4.3 m/sec. At this speed, and in areas of high noise and using low echolocation source levels, a harbour porpoise may not be able to detect either a monofilament or barium sulphate net before making contact with the net. Even so, our predictions should be taken as only an indicator of detection range because *Phocoena*-like clicks were not used to estimate harbour porpoise detection distances. TS values from both dolphin and harbor porpoise signals are predicted to be very similar, however (Au, 1994). Thus, it is valid to apply TS results obtained with a dolphin signal to predict harbour porpoise detection ranges as long as the basis of the prediction is understood.

Bottlenose dolphins generally emit higher echolocation source levels than the harbour porpoise. Peak amplitudes of bottlenose dolphins have been measured from 170 to 210 dB re: 1μPa (Moore & Pawloski, 1990). When source levels are high, detection distances may be as far as 80 m for both types of nets. When bottlenose dolphins emit echolocation clicks of higher SLs, a barium sulphate net may reduce bycatch entanglement rates over monofilament nets. It is important to note that the detection range depends on a log equation, so detection ranges vary quite a bit with source level and, thus, the detection range predicted for bottlenose dolphins can be as low as 6 m in noisy seas.

Bottlenose dolphins travel at speeds of up to 54 km/hr for short bursts of speed (Lockyer & Morris, 1987); however, for sustained effort and minimum energy expenditure, a dolphin would have to travel at an average 2.1 m/sec (Williams et al., 1992). Observations of a wild lone dolphin estimated average speed to be 10-20 km/hr or about 2.7-5.5 m/sec (Lockyer & Morris, 1987). When traveling at lower velocities (just over 2 m/sec), bottlenose dolphins should be able to detect a gillnet and change course before it contacts the net, even when its peak SL is only 170 dB. When feeding and presumably traveling at greater speeds (5 m/sec), this may still be possible. If the animal happens to make a burst of speed at the wrong time, however, the animal might be unable to detect a net in time to avoid it.

At lower peak source levels, the net material may become more important. For instance, at lower velocities, when the source level is 180 dB, noise level is 27 dB, and angle of incidence is 20°, the barium sulphate net was predicted to be detected 3 m further or almost 1 s sooner than a nylon net. At a 170 dB source level, 20° from normal incidence, and 33 dB noise level, the difference in predicted detection range is 4 m, or almost 2 s more time to detect and avoid a barium sulphate net as opposed to a nylon net. These experimental nets may provide the extra distance needed for an animal to avoid entanglement. At higher source levels, it appears that echolocating animals may detect both nets at a reasonable distance.

It remains to be determined whether the reduced harbor porpoise bycatch observed when barium sulphate nets were used (Cox & Read, 2001; Trippel et al., 2003) was due to detection via echolocation and consequent avoidance or other factors. Because detection of a barium sulphate net by an echolocating animal might not always be possible, at least in time to avoid net contact, other nonmutually exclusive factors might have caused the observed reduction in harbour porpoise bycatch. Cox & Read (2001) suggested that stiffness or coloration may be the dominant factor in reduced bycatch. For example, nets constructed of stiffer line, such as barium sulphate infused nylon, may have a reduced tendency to collapse around and entangle a dolphin. Studies are necessary to explore these explanations. Further, the hypothesis that barium sulphate nets reduced bycatch by being more detectable relies on the assumption that the animal is echolocating or searching for an acoustic target. It is important to note that previous work has shown that these barium sulphate nets also significantly reduce seabird bycatch (Trippel et al., 2003) and also alleviate marine turtle bycatch. Thus, even if acoustic reflectivity does not appear to be the actual contributing factor to reducing bycatch in the gillnet fishery, barium sulphate nets show promise as a socially and economically feasible method of reducing incidental take of marine animals.

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