The repulsive and feeding-deterrent effects of electropositive metals on juvenile sandbar sharks (*Carcharhinus plumbeus*)

Richard Brill (contact author)[1]
Peter Bushnell[2]
Leonie Smith[3]
Coley Speaks[4]
Rumya Sundaram[2]
Eric Stroud[5]
John Wang[6]

Email address for contact author: rbrill@vims.edu

[1] Cooperative Marine Education
and Research Program
Northeast Fisheries Science Center
National Marine Fisheries Service, NOAA
166 Water Street
Woods Hole, Massachusetts, 02543

Present address: Virginia Institute
of Marine Science
PO Box 1346 (mail)
Route 1208 Greate Rd.
Gloucester Point,
Virginia 23062

[2] Department of Biological Sciences
Indiana University South Bend
1700 Mishawaka Avenue
South Bend, Indiana, 46634

[3] Department of Biological Science
Bangor University
Bangor Gwynedd, LL57 2DG, UK

[4] Department of Marine Science
Hampton University
Hampton, Virginia, 23668

[5] Shark Defense Technologies, LLC
P.O. Box 2593
Oak Ridge, New Jersey 07438

[6] Joint Institute for Marine and Atmospheric
Research University of Hawai'i at Manoa
1000 Pope Road
Honolulu, Hawaii, 96822

Abstract—Reducing shark bycatch and depredation (i.e., damage caused by sharks to gear, bait, and desired fish species) in pelagic longline fisheries targeting tunas and swordfish is a priority. Electropositive metals (i.e., a mixture of the lanthanide elements lanthanum, cerium, neodymium, and praseodymium) have been shown to deter spiny dogfish (*Squalus acanthias,* primarily a coastal species) from attacking bait, presumably because of interactions with the electroreceptive system of this shark. We undertook to determine the possible effectiveness of electropositive metals for reducing the interactions of pelagic sharks with longline gear, using sandbar sharks (*Carcharhinus plumbeus,* family Carcharhinidae) as a model species. The presence of electropositive metal deterred feeding in groups of juvenile sandbar sharks and altered the swimming patterns of individuals in the absence of food motivation (these individuals generally avoided approaching electropositive metal closer than ~100 cm). The former effect was relatively short-lived however; primarily (we assume) because competition with other individuals increased feeding motivation. In field trials with bottom longline gear, electropositive metal placed within ~10 cm of the hooks reduced the catch of sandbar sharks by approximately two thirds, compared to the catch on hooks in the proximity of plastic pieces of similar dimensions. Electropositive metals therefore appear to have the potential to reduce shark interactions in pelagic longline fisheries, although the optimal mass, shape, composition, and distance to baited hooks remain to be determined.

Manuscript submitted 31 October 2008.
Manuscript accepted 2 March 2009.
Fish. Bull. 107:298–307 (2009).

The worldwide bycatch of sharks is estimated to be 260,000–300,000 metric tons annually (11.6 to 12.7 million individual sharks) (Bonfil, 1994; Camhi et al., 1998). In pelagic longline fisheries targeting tunas and swordfish, it is not uncommon for the number of sharks caught to exceed that of the desired fish species (Stevens, 1992; Bonfil, 1994; Gilman et al., 2008). Shark populations are especially vulnerable to high rates of fishing mortality because of their slow growth rates, low reproductive output, and late sexual maturity. Once depleted, they also generally have slow rates of recovery because of these characteristics (Smith and Snow, 1998; Chen and Yuan, 2006). Scalloped hammerhead (*Sphyrna lewini*), oceanic whitetip (*Carcharhinus longimanus*), and tiger shark (*Galeocerdo cuvier*) populations have already decreased within the range from 60% to 99% of their historical biomass (Baum et al., 2003; Baum and Myers, 2004; Gilman et al., 2008), and these species are now included on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN, 2008). Such severe reductions in elasmobranch populations have the potential to detrimentally restructure marine ecosystems (Jackson et al., 2001; Myers and Worm, 2003; Worm et al., 2006; Myers et al., 2007). Survival rates of pelagic sharks released from longline gear appear high for animals that are not moribund when the gear is retrieved (Moyes et al., 2006). Nonetheless, reduction of both shark bycatch and depredation (i.e., shark damage to longline gear, bait, and desired fish species) is considered a priority (Gilman et al., 2008, Mandelman et al., 2008).

Sharks (but not the large pelagic teleosts targeted by longline fisheries) possess a unique sensory system based on the ampullae of Lorenzini that can detect electric field gradients as small as 5 nV/cm (Haine et al., 2001). These ampullary receptors are most sensitive to frequencies from 1 to 8 Hz (Montgomery, 1988), are capable of detecting weak electric fields generated by neuromuscular activity, and can guide sharks to prey in the absence of other sensory stimuli (Kajiura and Holland, 2002; Kajiura, 2003; Collin and Whitehead, 2004). It should be possible, therefore, to develop effective deterrent procedures that could take advantage of the sharks' electroreceptive sense. The procedures could then decrease the bycatch and incidental mortality of sharks and increase fishing efficiency and yield of the desired fish species. Strong electric fields have been shown to deter approaching sharks, presumably by overloading their electrosensory modality (Smith, 1974, 1991; Cliff and Dudley, 1992). However, currently available electronic devices for achieving this behavioral response are designed to protect humans and aquaculture structures from shark attack and are large, expensive, and not practical for deployment on longline fishing gear. There are no data on the minimum field strength needed to achieve electrosensory repulsion.

Electropositive metals (generally mixtures of the lanthanide elements praseodymium, neodymium, cerium, lanthanum, samarium, and yttrium) rouse juvenile lemon sharks (*Negaprion brevirostris*), nurse sharks (*Ginglymostoma cirratum*), and spiny dogfish sharks (*Squalus acanthias*) from tonic immobility when brought close to the head (Stoner and Kaimmer, 2008). Electropositive metals have also been shown to deter spiny dogfish sharks from attacking baits in a tank study (Stoner and Kaimmer, 2008), and to reduce the catch of this species by 19% on bottom longline gear (Kaimmer and Stoner, 2008). Electropositive metals are assumed to stimulate the electroreceptive system by giving up cations to the more electronegative skin of the elasmobranchs (Rice, 2008; Stoner and Kaimmer, 2008), although the exact mechanisms responsible for repulsion are not known.

Our studies are designed to determine if electropositive metals affect the behaviors of juvenile sandbar sharks (*Carcharhinus plumbeus*) under both laboratory and field conditions. Sandbar sharks are highly suitable for this line of research because they do well and feed readily in captivity. They are also an obligatory ram-ventilating species and their constant forward motion makes it easier to measure changes in swimming patterns caused by electropositive metals, compared to species that remain motionless on the bottom for extended periods. More importantly, although primarily a coastal species (Conrath, 2005; Conrath and Musick, 2008), the sandbar shark is a member of the family *Carcharhinidae* (requiem sharks), which includes many of the other shark species that frequently interact with pelagic longline gear (Mandelman et al., 2008). Results with sandbar sharks should, therefore, provide a good indication of the efficacy of electropositive metals for reducing shark bycatch in pelagic longline fisheries.

Our experiments with captive sandbar sharks include tests of the ability of electropositive metals to influence the swimming patterns of individual animals in the absence of food motivation and to repel sharks from pieces of cut bait. The former is intended to quantify repulsive distances, and both are intended to provide data directly comparable with those obtained previously with spiny dogfish sharks (Stoner and Kaimmer, 2008; Tallack and Mandelman, in press). Our deployment of longline fishing gear in a tidal lagoon system used as a nursery area by juvenile sandbar sharks (Conrath, 2005; Conrath and Musick, 2007) tested the ability of electropositive metal to deter sharks under field conditions and provided data comparable to data from recent studies where spiny dogfish sharks were targeted by a similar method (Kaimmer and Stoner, 2008; Tallack and Mandelman, in press).

Materials and methods

Experiments with captive animals were conducted during the summer months (June through August 2007) at the Virginia Institute of Marine Science, Eastern Shore Laboratory, in Wachapreague, Virginia. Juvenile sandbar sharks weighting up to ~5 kg (i.e., neonates to approximately 5 years old; Casey and Natanson, 1992) were captured with standard recreational hook-and-line fishing gear in the surrounding tidal lagoon system and transported to an outdoor circular fiberglass tank (7 m diameter, 1.8 m deep) as described previously (Brill et. al., 2008). The tank was supplied with sea water pumped from the adjacent tidal lagoon which was passed through sand filters to remove suspended particles, as well as phytoplankton and fouling organisms. Water from the holding tank was also continuously circulated through a separate set of sand filters, ultraviolet sterilizer, biofilter, and protein skimmer. Tank temperature and salinity over the course of the study (22–29°C and 30–33‰, respectively) reflected that of the adjacent tidal lagoon. When not part of an active experiment, the sharks were fed pieces of cut menhaden (*Brevoortia tyrannus*) every other day. All sharks were actively feeding before use in any trials.

Repulsion experiments with individual sharks

Experiments were performed on 10 sharks, and individuals were not used more than once. For each replicate, an individual shark was transferred from the main holding tank to a smaller vinyl circular indoor test tank (3.6 m diameter, 0.67 m water depth) and allowed to acclimate for 24 hours. The test tank was supplied with seawater pumped from the adjacent tidal lagoon which was passed through sand filters. Temperature and salinity ranged from 22° to 29°C and from 30‰ to 33‰ over the course of the study.

An experiment consisted of three one-hr periods. At the start of the first hour, a string of three lead fishing weights was suspended in the tank to allow the shark to acclimate to the presence of a new visual stimulus. At the start of the second hour the string of lead fishing weights was quietly removed and immediately replaced with either a string of three electropositive metal bars, or the string of lead fishing weights was placed back into the tank. This choice was randomized. At the start of the third hour, the string of electropositive metal bars or lead fishing weights was removed and replaced with the other. Only the video records from the second and third hours (i.e., one hour in the presence of electropositive metal bars and one hour in the presence of lead fishing weights) were subsequently analyzed.

The three electropositive metal bars (~2 cm × 2 cm × 10 cm) comprised neodymium (76%), praseodymium (23%), and minor amounts (<0.04%) of cerium, lanthanum, samarium, and yttrium (Hefa Rare Earth, Vancouver, Canada). The three lead fishing weights had similar dimensions to those of the electropositive metal bars. The strings electropositive metal bars and lead fishing weights were constructed by using single pieces of nylon monofilament fishing line and were suspended in the tank at a position approximately 35 cm from the tank sidewall (Fig. 1). This lateral position was chosen because preliminary observations had shown that juvenile sandbar sharks swam predominately in a circular pattern near the tank wall. There was sufficient space, however, for the fish to pass easily between the nylon line (holding the electropositive metal bars or lead fishing weights) and the tank wall. Individual electropositive metal bars and lead fishing weights were attached to the nylon fishing line so as to be at approximately 16, 32, and 48 cm below the surface when suspended in the tank.

A digital monochrome video camera (IDS Imaging Development Systems Inc., Cambridge, MA) equipped with a wide angle lens was used to acquire a continuous record (on a laptop computer) of the swimming patterns of each shark. The camera was mounted on the laboratory ceiling, over the center of the tank, approximately 1.5 m above the water surface. This allowed an almost complete view of the tank, although small areas at the 12 and 6 o'clock positions remained out of frame because of the maximum height of the digital video camera imposed by the laboratory ceiling. The locations of the sharks were subsequently digitized (*x, y* coordinate system) at one-second intervals from the video record by using Lolitrack automated video analysis software (Loligo Systems, Tjele, Denmark). The software generally digitized the broadest area of the shark from the dorsal view (i.e., the area between the pectoral fins and first dorsal fin).

Shark positions were translated into quantifiable behaviors by calculating the distances between the sharks and the electropositive metal or lead weights from the one-second interval location records. These data were summarized by compiling frequency distributions with 5-cm bins. Fractional values for each distance bin were calculated from the total number of position estimates for each animal when the electropositive metal bars or lead fishing weights were present in the tank. The fractional bins were averaged across all fish. A two-way (treatment×distance bin) repeated measures analysis of variance (ANOVA) procedure was used to test for differences in the frequency distributions (with the use of arcsine transformed percentage data), with *post hoc* tests for significant differences between individual bins (Sigma Stat, vera. 3.0.1, Systat Software, Inc., San Jose, CA). The significance level for all tests was $P < 0.05$.

The digital position records were also used to calculate swimming speeds, which were subsequently segregated into swimming speeds recorded when the fish was within 100 cm of the electropositive metal bars or lead fishing weights, and into swimming speeds recorded

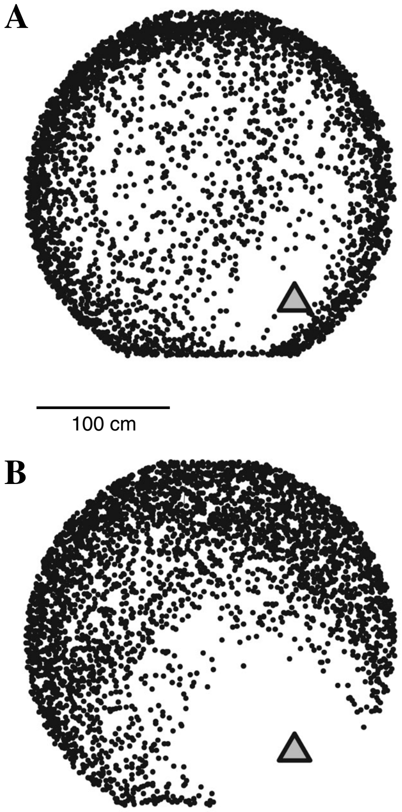

Figure 1

Positions of a juvenile sandbar shark (*Carcharhinus plumbeus*) at 1-sec intervals obtained with Lolitrack automated video analysis software (Loligo Systems, Tjele, Denmark). Three lead fishing weights (**A**) or three electropositive metal bars (**B**) were suspended in the tank using monofilament fishing line at the position indicated by the triangles. The video record was acquired with a digital video camera mounted directly above the center of a vinyl circular tank (3.6 m diameter, 0.67 m water depth). Small portions of the tank at the 12 o'clock and 6 o'clock positions were out of frame because of the maximum available height of the laboratory ceiling where the video camera was positioned.

when the fish was further than 100 cm from the electropositive metal bars or lead fishing weights.

Feeding deterrent experiments

Groups of sharks maintained in the outdoor circular fiberglass holding tank were used to determine the ability of electropositive metals to deter sharks from attacking bait. Individual pieces of cut menhaden were placed 30 cm below a single electropositive metal bar (~2 cm × 2 cm × 10 cm and of the same composition described previously) by using a monofilament nylon fishing line. For control trials, pieces of cut menhaden were placed 30 cm below a stainless steel bolt of approximately the same dimensions as the electropositive metal bar. Baits were attached to the monofilament line with light twine that allowed the bait to be removed by the sharks with moderate effort. Hooks were not used because of the risk of injuring the sharks and the likelihood that hooking would influence the willingness of the sharks to attack baits in subsequent trials. The line (with the bait and stainless steel bolt or electropositive metal bar) was suspended near the center of the tank and in approximately the middle of the water column. The order of presentation was randomized.

During each trial, the line was immediately removed from the water after the bait was attacked and the time from presentation to attack was recorded. The line was also removed from the water if the bait was not attacked within three minutes. In either case, five minutes were allowed before the next trial was begun. Because of the number of sharks in the tank, the rapidity of the attacks, and the frequent shark-shark interactions, it was not possible to identify which individual attacked the bait or to quantify specific changes in behavior as the bait was approached.

Two separate series of experiments were conducted. In the first, 14 actively feeding juvenile sandbar sharks were present in the holding tank and 14 trials (seven with the electropositive metal and seven with the stainless steel bolt) were conducted every other day over a 14-d period. The sharks were fed to satiation at the end of each set of trials, but not on the days between experiments. Two additional sessions were run one week after the completion of the first 14 sessions. The original group of sharks was then released and replaced with seven naive individuals. Eight trials (four with the electropositive metal bar and four with the stainless steel bolt) were conducted every other day, over a 12-day period. As in the previous experiments, the sharks were fed to satiation at the end of each set of trials, but not on the days between experiments. Feeding trials were run at approximately the same time everyday (late afternoon).

Longline experiments

Bottom longline fishing gear was used to test the ability of electropositive metal to influence shark catch rates in the field. Longline trials were conducted during the summer months (July and August 2008). The gear was deployed a total of 26 times (two deployments per day) and all deployments except for one were in the tidal lagoon system adjacent to the eastern shore of Virginia (an area of tidal creeks and broad marshes separated from the Atlantic Ocean by a series of barrier islands to the east). One longline set was made in the ocean immediately offshore of the barrier islands. All longline sets were conducted during daylight hours and the gear retrieved after two hours when conditions permitted. Gear deployment schedules were primarily based on weather, as well as crew and vessel availability, rather than on time of day or tidal state. Experiments were generally not undertaken on consecutive days.

Approximately 40 hooks were deployed during each set. The monofilament dropper lines were two meters long and were terminated with steel circle hooks (10/0 or 11/0) baited with pieces of menhaden. Dropper lines were connected to the mainline at 10-m intervals to help ensure that each dropper fished independently. Small pieces (approximately 30–70 g initial weight) of electropositive metal comprising lanthanum (28%), cerium (53%), neodymium (15%), and praseodymium (4%) were attached to the dropper lines approximately 10 cm from the hook by using plastic zip ties. The electropositive metal pieces, cut in cross section from the ingots supplied by the distributor (Hefa Rare Earth, Vancouver, Canada), were approximately 2-cm thick plates (~30–60 cm^2 surface area per side). Plastic pieces, of approximately the same shape and surface area were attached at the same positions to control for any visual deterrent or mechanical effects. Lines with electropositive metal near the hook and with a plastic piece near the hook were attached to the mainline in an alternating pattern and in equal numbers during each gear deployment. This arrangement allowed the resultant catch data to be analyzed with a chi-square procedure based on the expectation that equal numbers of sharks would be caught on hooks near a plastic piece or on hooks near electropositive metal, if the latter did not alter shark behaviors.

Captured sharks were brought into the boat, hooks were cut in two places to help ensure that they would be shed quickly, standard length was measured, and sex was noted. These sharks were then immediately released. Clearnose skates (*Raja eglanteria*) were treated similarly. Large rays (orders: Rajiformes and Myliobatiformes) were released without removing them from the water to ensure crew safety, and were therefore usually not identified to species.

Results

Repulsion experiments with individual sharks

In the presence of the lead fishing weights, sharks swam predominately around the periphery of the tank, showed essentially no avoidance response, and frequently passed between the lead fishing weights and tank wall. In contrast, sharks generally avoided approaching electropositive metal bars, which precluded them from passing between the electropositive metal bars and the tank wall. The locations of a single sandbar shark typifying these behaviors are shown in Figure 1.

The frequency distributions of positions in relation to the lead fishing weights or electropositive metal bars demonstrate avoidance of the latter by the sharks (Fig. 2). Significantly fewer positions were recorded within approximately 100 cm of the electropositive metal bars, and significantly more positions at the maximum distances (further than approximately 200 cm from the electropositive metal bars). The frequency distributions under both circumstances increased with distance and truncated sharply at the greatest distances because of simple positional geometry and the limitations imposed by the dimensions of the circular test tank.

The swimming speed data were not normally distributed and are therefore shown as box and whisker plots (Fig. 3). There appeared to be a tendency for swimming speeds to be greater in proximity to the electropositive metal bars than under the other circumstances. However, the small differences and extreme variability precluded statistically significant differences.

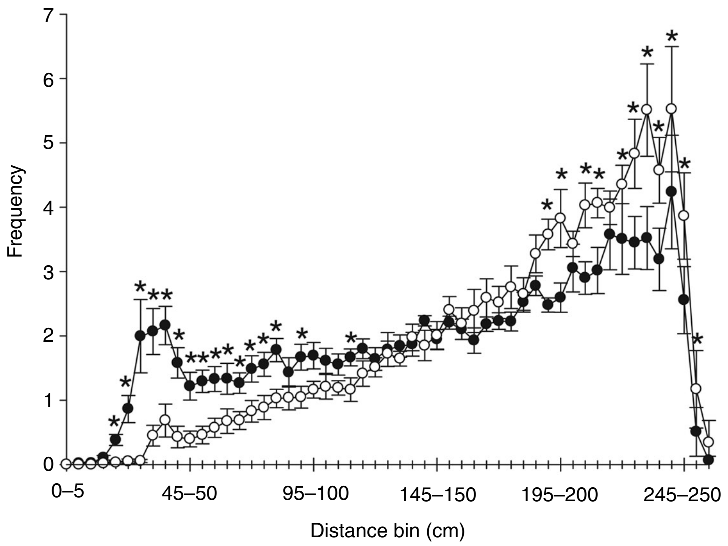

Figure 2

Frequency distributions (based on 5-cm bins) of the observed distances in relation to lead fishing weights (filled circles) or electropositive metal (open circles) calculated at 1-sec intervals from the video records of juvenile sandbar sharks (*Carcharhinus plumbeus,* n=10). When compared to the lead weights, significantly fewer (indicated by *, two-way repeated measures ANOVA, P <0.05) shark positions were recorded within 100 cm of electropositive meta, whereas more positions were recorded at distances more than approximately 200 cm from electropositive metal.

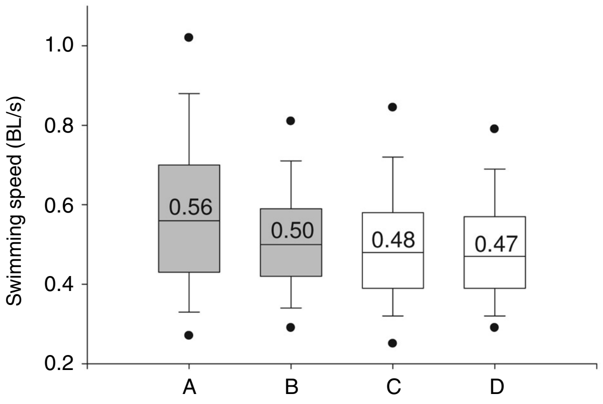

Figure 3

Median swimming speeds in body lengths per second (BL/s) when juvenile sandbar sharks (*Carcharhinus plumbeus*) were within 100 cm of electropositive metal (**A**), more than 100 cm from electropositive metal (**B**), within 100 cm of lead fishing weights (**C**), and more than 100 cm from lead fishing weights (**D**). The high variability precluded statistically significant differences, but there appears to be a trend for fish to swim faster in proximity to electropositive metal than under the other circumstances. Limits of boxes show the 25th and 75th percentiles, the error bars the 90th and 10th percentiles, and the single points the 95th and 5th percentiles.

Feeding deterrent experiments

Bait pieces located approximately 30 cm from a stainless steel bolt were generally attacked within 30 seconds of presentation (Figs. 4 and 5). In contrast, sharks did not attack baits located in proximity of an electropositive metal bar within three minutes, at least during the initial trials. When the repulsive effect was evident, sharks would rapidly approach the bait, flinch, turn sharply, and rapidly depart. Although we were not able to quantify these behaviors, they matched the responses of spiny dogfish sharks under similar circumstances described by Stoner and Kaimmer (2008) and mirrored the apparent changes in swimming speeds of individual sharks near electropositive metal (Fig. 3).

When 14 sharks were present in the tank (Fig. 4), the repulsive effect extinguished fairly suddenly during day 2, but reappeared during the initial trials on day 4, and again during the initial trials on days 10 and 21. Because it was impossible to identify individuals, it is unknown if only one or a few sharks overcame the deterrent effect of electropositive metal. The repulsive effect did not reappear after a one-week period where trials were not run; indicating that once tolerance of electropositive metal is learned it is retained at least over the short term.

During the second set of experiments with fewer sharks in the tank (seven animals versus 14), the deterrent effect of electropositive metal was apparent until day 8 and it did not completely disappear until day 12 (Fig. 5).

Longline trial experiments

Of the juvenile sandbar sharks captured, 39 were female, 26 were male, and there was one individual where sex was not recorded. Sharks ranged in size (standard length) from 47 to 130 cm, and had a median length of 72.5 cm. Only one cownose ray (*Rhinoptera bonasus*) was captured, the other rays were either *Gymnura* spp. or *Dasyatis* spp. Two Atlantic sharpnose sharks (*Rhizoprionodon terraenovae*) and nine clearnose skates (*Raja eglanteria*) were captured during the one gear deployment made outside the lagoon system.

The ratio of sharks caught on hooks near plastic to sharks caught on hooks near electropositive metal (2.6:1) was significantly different from the predicted ratio of 1:1 if the presence of the latter had no deterrent effect (chi square test P=0.001, df=1, χ^2=10.78). In other words, electropositive metal near the hooks reduced the catch rates of sharks by 62% (Table 1). In contrast, the numbers of rays caught on hooks near plastic and on hooks near electropositive metal were not significantly different from the expected ratio of 1:1 (chi square test P=0.67, df=1, χ^2=0.39), indicating that the presence of electropositive metal had no deterrent effect. The low number of clearnose skates captured precluded any definitive conclusions. However, the essentially equal numbers of skates caught on each hook type (Table 1) implies that the presence of electropositive metal does not deter this species.

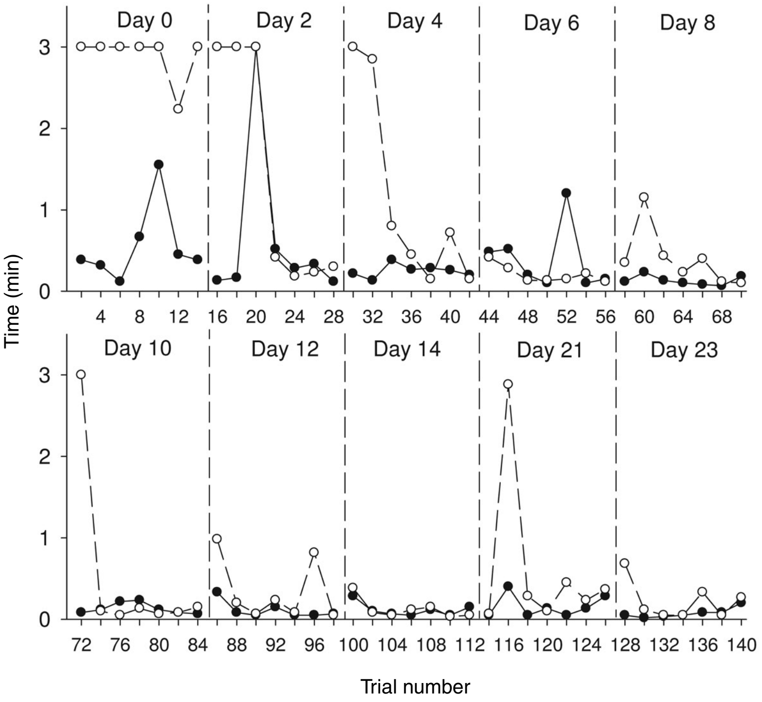

Figure 4

Time taken for cut pieces of menhaden (*Brevoortia tyrannus*) to be attacked when suspended 30 cm below a stainless steel bolt (filled circles) or an electropositive metal bar (open circles). The line was removed from the tank if the bait was not attacked within three minutes. Trials were conducted with 14 juvenile sandbar sharks (*Carcharhinus plumbeus*) maintained in a circular fiberglass tank (7 m diameter, 1.8 m deep). Fourteen trials (seven with the electropositive metal bar and seven with the stainless steel bolt) were conducted every other day for the first 14 days, suspended for seven days, and then two additional trials were run to test whether the electropositive metal near the bait, as seen during the initial trails, would continue to deter the sharks.

Table 1

Catch of sharks (primarily juvenile sandbar sharks, *Carcharhinus plumbeus*), rays (primarily *Gymnura* spp. and *Dasyatis* spp.) and clearnose skates (*Raja eglanteria*) by bottom longline gear. Pieces of electropositive metal, or pieces of plastic of similar dimensions, were placed within 10 cm of the hooks. Hooks in proximity to electropositive metal or to plastic pieces were deployed in equal numbers and in an alternating pattern during each set.

	Sharks	Rays	Skates
Hooks near electropositive metal	16	10	4
Hooks near plastic	42	13	5

Discussion

Repulsion experiments with individual sharks

Because juvenile sandbar sharks showed no reactions to lead fishing weights (other than to avoid running into them), we concluded that lead fishing weights exert no significant repulsive effect. In contrast, juvenile sandbar sharks generally avoided approaching the electropositive metal bars presumably because they produce mild irritation. Whether this irritation is chemical or electrical (i.e., stimulation of the sharks electroreceptive system) is unknown. Given the apparent definitive

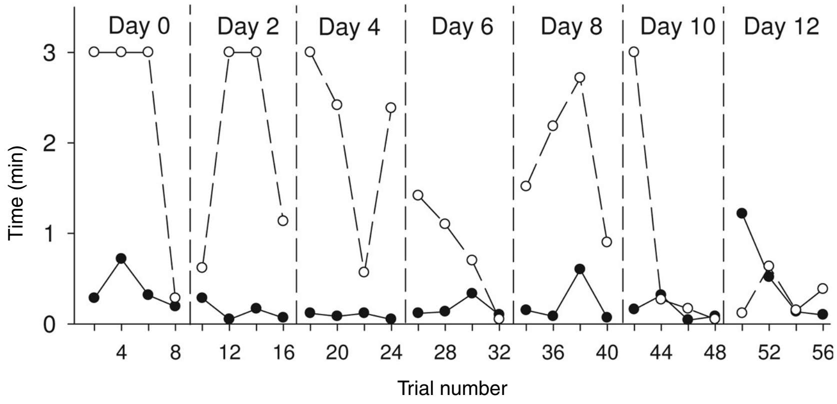

Figure 5

Time taken for cut pieces of menhaden to be attacked when suspended 30 cm below a stainless steel bolt (filled circles) or an electropositive metal bar (open circles). The line was removed from the tank if the bait was not attacked within three minutes. During these trials, seven juvenile sandbar sharks (*Carcharhinus plumbeus*) were maintained in a circular fiberglass tank (7 m diameter, 1.8 m deep). Eight trials (four with the electropositive metal bar and four with the stainless steel bolt) were conducted every other day. The deterrent effect of electropositive metal was present over a greater number of days compared with the previous situation when 14 sharks were present in the tank. The difference is assumed to be due to increased competition for food which limited the repulsive effect of electropositive metal in the latter circumstance.

boundary of the area that is avoided (Fig. 1), we surmise the latter to be the case. Stoner and Kaimmer (2008) reach similar conclusions with respect the deterrent effect of electropositive metal on spiny dogfish sharks. The effective range of deterrence (~100 cm) for juvenile sandbar sharks is, however, considerably larger than that for spiny dogfish sharks (10–20 cm) (Stoner and Kaimmer, 2008). Whether this is due to differences in water temperatures (~10°C for spiny dogfish sharks versus 22–29°C for juvenile sandbar sharks), mass or shape of bars, specific composition of the electropositive metals, or species differences remains to be determined. The number of electrosensory pores present in sandbar sharks is approximately twice that in spiny dogfish sharks (2317 versus 1262, respectively; Cornett, 2006) which may explain the difference in the distances that these sharks were deterred.

Because of the limited range of deterrence, electropositive metal would have to be placed near every hook in pelagic longline gear, although it appears that it could be placed at distances that are unlikely to interfere with capture of the targeted fishes. It is unknown if electropositive metal could protect hooked fishes from depredation by sharks, which is a significant problem (Gilman et al., 2008; Mandelman et al., 2008).

Feeding deterrent experiments

Stoner and Kaimmer (2008) theorize that the presence of electropositive metal is irritating or possibly interferes with the ability of sharks to locate a food item. We hypothesize that irritation is the more likely reason the bait was not attacked within three minutes during the initial trials with electropositive metal in our feeding experiments. The tank was brightly lit and the water was essentially free of suspended particles because of the extensive filtration. We therefore contend that the sandbar sharks located the bait primarily by vision (although olfaction may also be involved). Moreover, the pieces of cut menhaden would obviously not have the bio-electric signals emitted by living organisms (Haine et al., 2001). Further investigation into the exact mechanism(s) underlying the effect of electropositive metals as is clearly warranted.

Our specific experimental procedures were designed to ensure that feeding motivation remained high and thus to minimize the influence of feeding motivation on our results. Any influence of competition on feeding motivation could not be controlled however, except by altering the number of sharks in the tank. Competition is well known to increase feeding motivation (Ryer and Olla, 1991; Eklov, 1992) and we assume that it likewise lessens the deterrent effects of electropositive metal. Increased feeding motivation due to competition could, therefore, explain the short-lived deterrent effects of electropositive metal when 14 sharks are present in the tank. Our observation that the deterrent effect lasts longer during the trials when only seven sharks are present supports this contention.

Our data also imply that tolerance of electropositive metals can be learned, and that this learned behavior is retained for at least seven days. It is unknown how often individual sharks encounter pelagic longline gear, but it is unlikely to be anywhere near the frequency of our feeding trials with captive sandbar sharks. For this reason we propose that learned tolerance of electropositive metals will unlikely diminish their deterrent effect when used with pelagic longline fishing gear.

Longline trial experiments

From our longline catch data (Table 1), it is clear that the presence of electropositive metal near hooks is a strong deterrent to juvenile sandbar sharks, but not to rays. In recent studies where similar methods were used resulted in either a smaller reduction in catch rates (20%) of spiny dogfish sharks (Kaimmer and Stoner, 2008) than we observed, or in no statistically significant reduction (Tallack and Mandelman, in press). Surprisingly, Kaimmer and Stoner (2008) also recorded a large reduction (46%) in the catch of longnose skates (*Raja rhina*) due the presence of electropositive metal near longline hooks, whereas we saw no indication of a repulsive effect on clearnose skates.

The sensitivity of the electroreceptor system has been studied in a broad range of elasmobranchs (reviewed by Montgomery, 1988; Kalmijn, 2003) and there is no evidence of a lesser sensitivity in rays when compared to sharks. More specifically, the sensitivity of the electroreceptor system in the sandbar shark, the blacktip reef shark (*Carcharhinus melanopterus*, family Carcharhinidae), and the mangrove whipray (*Himantura granulata*, family Dasyatidae) are roughly equivalent (1 to 4 nV/cm; Haine et al., 2001; Kajiura and Holland, 2002). By implication, therefore, the catch rates of all the elasmobranch species interacting with the longline gear should be reduced equally, but clearly are not. The species-specific responses of sharks, skates, and rays to electropositive metal may reside at the receptor level (Tricas and New, 1998), the level of central processing, or simply reflect different behavioral tolerance related to feeding motivation. Kaimmer and Stoner (2008) and Tallack and Mandelman (in press) both speculate that the abundance of dogfish results in strong competition for food and increased aggressiveness, and that these limit the repulsive effect of electropositive metal. Our results showing a longer lasting repulsive effect of electropositive metal during feeding experiments when fewer sharks are present in the tank (Fig. 4 and 5) support this contention. Assessing the specific differences between various species of sharks, skates, and rays could clearly be a fruitful area of investigation.

Health and environmental safety concerns with use of electropositive metals in fisheries

The electropositive metals used in our experiments are mixtures of lanthanide elements (e.g., lanthanum, cerium, neodymium, and praseodymium) that are collectively known as the "rare earth" elements, although they are not particularly rare (Bulman, 1994). Lanthanide elements are generally considered nontoxic to mammals primarily because they are not easily absorbed if ingested (Haley, 1965; Bulman, 1994). Their accumulation in animal tissue is therefore generally very low to negligible even for animals in long-term feeding trials, and transfer to humans through foodstuffs is likewise very low (Redling, 2006). We therefore conclude that the use of electropositive metals as elasmobranch deterrents would pose little if any toxicity to fishing crews handling the material, or to the food safety of targeted fish species. Lanthanide elements are also used as crop fertilizers and animal feed performance boosters for poultry, sheep, cattle, pigs, fish, and prawns; and in a variety of medical applications such as antimicrobial agents, MRI imaging, burn and cancer treatments, and for countering hyperphosphatemia in renal dialysis patients (Fricker, 2006).

Lanthanide elements injected intravenously can be toxic, however, because they cross cell membranes by passing through calcium channels, and because they have high affinity for calcium binding sites on biological molecules (Haley, 1965; Bulman, 1994). It is therefore at least possible that extensive distribution of lanthanide elements in the marine environment could impact invertebrate species (e.g., mollusks and crustaceans) that routinely incorporate calcium into their shells and exoskeletons.

Conclusion and future directions

Improving gear selectivity (i.e., reducing shark bycatch and depredation) is considered a high priority in pelagic longline fisheries because of its ecological and economic benefits (Gilman et al., 2008, Mandelman et al., 2008). The use of electropositive metals appears promising in this regard. However, the specific composition, mass, and shape of the composite metal deterrent representing an optimal compromise between a high deterrent effect and a long useable durability in seawater remain to be ascertained. In conjunction with at-sea trials, behavioral assays with captive juvenile sandbar sharks would provide an effective means for testing and optimizing the use of electropositive metals.

Acknowledgments

Funding for this project was provided by the Fishery Biology and Stock Assessment Division, Pacific Islands Fisheries Science Center, National Marine Fisheries Service, NOAA; the National Shark Research Consortium (NOAA/NMFS Grant no. NA17FL2813); and an Indiana University South Bend SMART grant to R. Sundaram. We also gratefully acknowledge the entire staff of the Virginia Institute of Marine Science Eastern Shore Laboratory for their continuing and genuine hospitality and technical support. All animal capture, maintenance, and handling procedures were approved by the College

of William and Mary Institutional Animal Care and Use Committee and comply with all current applicable laws of the United States of America. This is contribution 2991 from the Virginia Institute of Marine Science.

Literature cited

Baum, J. K., R. A. Myers, D. G. Kehler, B. Worm, S. J. Harley, and P. A. Doherty.
2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science 299:389–392.

Baum, J. K., and R. A. Myers.
2004. Shifting baselines and the decline of pelagic sharks in the Gulf of Mexico. Ecol. Lett. 7:135–145.

Bonfil, R.
1994. Overview of world elasmobranch fisheries. FAO Fisheries Tech. Paper 341, 119 p. FAO, Rome.

Brill, R., P. Bushnell, S. Schroff, R. Seifert, and M. Galvin.
2008. Effects of anaerobic exercise accompanying catch-and-release fishing on blood-oxygen affinity of the sandbar shark (*Carcharhinus plumbeus*, Nardo). J. Exp. Mar. Biol. Ecol. 34:132–143.

Bulman, R. A.
1994. Europium and other lanthanides. *In* Handbook on metals in clinical and analytical chemistry (H. G. Seiler, A. Sigel, and H. Sigel, eds.), p. 351–363. Marcel Dekker, Inc., New York, NY.

Camhi, M., S. Fowler, J. Musick, A. Bräutigam, and S. Fordham.
1998. Sharks and their relatives—ecology and conservation. Occasional Paper of the IUCN Species Survival Commission no. 20, 39 p.

Casey, J. G., and L. J. Natanson.
1992. Revised estimates of age and growth of the sandbar shark (*Carcharhinus plumbeus*) from the Western North Atlantic. Can. J. Fish. Aquat. Sci. 49:1474–1477.

Chen. P., and W. Yuan.
2006. Demographic analysis based on the growth parameter of sharks. Fish. Res. 78:374–379.

Cliff, G., and S. F. J. Dudley.
1992. Protection against shark attack in South Africa, 1952–90. Aust. J. Mar. Freshw. Res. 43:263–272.

Collin, S. P., and D. Whitehead.
2004. The functional roles of electroreception in non-electric fishes. Anim. Biol. 54:1–25.

Conrath, C.
2005. Nursery delineation, movement patterns, and migration of the sandbar shark, *Carcharhimus plumbeus*, in the eastern shore of Virginia coastal bays and lagoons. Ph. D. diss., 184 p. Virginia Institute of Marine Science, Gloucester Point, VA.

Conrath, C. L., and J. A. Musick.
2007. The sandbar shark summer nursery within bays and lagoon of the eastern shore of Virginia. Trans. Am. Fish. Soc. 136:999–1007.
2008. Investigations into depth and temperature habitat utilization and overwintering grounds of juvenile sandbar sharks, *Carcharhinus plumbeus*: the importance of near shore North Carolina waters. Environ. Biol. Fish. 82:123–131.

Cornett, A. D.
2006. Ecomorphology of shark electroreceptors. M. S. thesis, 102 p. Florida Atlantic Univ., Boca Raton, FL.

Eklov, P.
1992. Group foraging versus solitary foraging efficiency in piscivorous predators: the perch, *Perca fluviatilis*, and pike, *Esox lucius*, patterns. Anim. Behav. 44:313–326.

Fricker, S. P.
2006. The therapeutic application of lanthanides. Chem. Soc. Rev. 35:524–533.

Gilman, E., S. Clarke, N. Brothers, J. Alfaro-Shigueto, J. Mandelman, J. Mangel, S. Petersen, S. Piovano, N. Thomson, P. Dalzell, M. Donoso, M. Goren, and T. Werner.
2008. Shark interactions in pelagic longline fisheries. Mar. Pol. 32:1–18.

Haine, O. S., P. V. Rid, and R. Rowe.
2001. Range of electrosensory detection of prey by *Carcharhinus melanopterus* and *Himantura garnulata*. Mar. Freshwat. Res. 52:291–296.

Haley, T.J.
1965. Pharmacology and toxicology of the rare earth elements. J. Pharm. Sci. 54:663–670.

IUCN (International Union for Conservation of Nature).
2008. IUCN Red List for Endangered Species. http://www.iucnredlist.org/ (accessed September, 2008).

Jackson J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, and R. R. Warner.
2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629–638.

Kaimmer, S., and A. W. Stoner.
2008. Field investigation of rare-earth metal as a deterrent to spiny dogfish in the Pacific halibut fishery. Fish. Res. 94:43–47.

Kajiura, S. M.
2003. Electroreception in neonatal bonnethead sharks, *Sphyrna tiburo*. Mar. Biol. 143:603–61.

Kajiura, S. M., and K. N. Holland.
2002. Electroreception in juvenile scalloped hammerhead and sandbar sharks. J. Exp. Biol. 205:3609–3621.

Kalmijn, A. J.
2003. Physical principles of electric, magnetic, and near-field acoustic orientation. *In* Sensory processes in aquatic environments (S. P. Collin and N. J. Marshall, eds.), p. 77–91. Springer-Verlag, New York, NY.

Mandelman, J. W., P. W. Cooper, T. B. Werner, and K. M. Legueux.
2008. Shark bycatch and depredation in the U.S. Atlantic pelagic longline fishery. Rev. Fish Biol. Fish. 18:427–442.

Montgomery, J. C.
1989. Sensory physiology. *In* Physiology of elasmobranch fishes (T. J. Shuttleworth, ed.), p. 79–98. Springer Verlag, New York, NY.

Moyes, C. D., N. Frugoso, M. K. Musyl, and R. W. Brill.
2006. Predicting postrelease survival in large pelagic fish. Trans. Am. Fish. Soc. 135:1389–1397.

Myers, R. A., J. K. Baum, T. D. Shepherd, S. P. Powers, and C. H. Peterson.
2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. Science 315:1846–1850.

Myers, R. A., and B. Worm.
2003. Rapid worldwide depletion of predatory fish communities. Nature 423:280–283.

Redling, K.
2006. Rare earth elements in agriculture: with emphasis on animal husbandry. Ph.D. diss., 326 p. Univ. Munchen, Munchen, Germany.

Rice, P.
2008. A shocking discovery: How electropositive metals (EPMs) work and their effects on elasmobranchs. *In* Shark Deterrent and Incidental Capture Workshop, April 10–11, 2008 (Y. Swimmer, J. H. Wang, and L. McNaughton, eds.). U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-PIFSC-16, 72 p.

Ryer, C. H., and B. L. Olla.
1991. Information transfer and the facilitation and inhibition of feeding and a schooling fish. Environ. Biol. Fish. 30:317–323.

Smith, E. D.
1974. Electro-physiology of the electrical shark-repellent. Trans. S. Afr. Inst. of Electr. Eng. 65:166–185.
1991. Electric shark-barrier: Power-electronics. Power Eng. J. 5:167–176.

Smith, S. E., and D. W. Snow.
1998. Intrinsic rebound potentials of 26 species of Pacific sharks. Aust. J. Mar. Freshw. Res. 49:663–678.

Stevens, J. D.
1992. Blue and mako sharks bycatch in the Japanese south-east longline fishery off southeastern Australia. Aust. J. Mar. Freshw. Res. 43:227–236.

Stoner, A. W., and S. M. Kaimmer.
2008. Reducing elasmobranch bycatch: laboratory investigation of rare earth metal and magnetic deterrents with spiny dogfish and Pacific halibut. Fish. Res. 92:162–168.

Tallack, S. M. L., and J. W. Mandelman.
In press. Do rare earth metals deter spiny dogfish? A feasibility study on the use of mischmetal to reduce the by catch of *Squalus acanthias* by hook gear in the Gulf of Maine (USA). ICES J. Mar. Sci.

Tricas, T. C., and J. C. New.
1998. Sensitivity and response dynamics of elasmobranch electrosensory primary afferent neurons to near threshold fields. J. Comp. Physiol. A Sens. Neural Behav. Physiol.182:89–101.

Worm, B., E. B. Barbier, N. Beaumont, J. E. Duffy, C. Folke, B. S. Halpern, J. B. C. Jackson, H. K. Lotze, F. Micheli, S. R. Palumbi, E. Sala, K. A. Selkoe, J. J. Stachowicz, and R. Watson.
2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314:787–790.