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Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery

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Abstract

The U.S. Atlantic coastal pelagic longline fishery that targets tunas and swordfish also interacts with a wide range of non-target species including billfishes and sea turtles. Preliminary studies indicate that a change in terminal gear from J-style hooks to circle hooks may reduce bycatch mortality, but the effects of this change on catch rates of target species are unclear. To evaluate this, we monitored catch composition, catch rates, hooking location, and number of fish alive at haulback during 85 sets in the fall and spring seasonal fisheries from a commercial vessel operating in the western North Atlantic. Circle (size 16/0, 0° offset) and J-style (size 9/0, 10° offset) hooks were deployed in an alternating fashion. Hook–time recorders were used to assess time at hooking and temperature–depth recorders to measure gear behavior. Catch rates for most species categories were not significantly different between hook types ($P < 0.05$), although circle hooks generally had higher tuna catch rates in the fall and lower swordfish catch rates in the spring. In the fall, both total catches and catches of pelagic rays were significantly higher on J-style hooks. Yellowfin tuna in the fall and dolphinfish in the spring caught on circle hooks were significantly larger than those caught on J-style hooks. In both seasonal fisheries, circle hooks caught fishes in the mouth more frequently than J-style hooks, which hooked more often in the throat or gut, although these differences between hook types were not statistically significant. Yellowfin tuna in the fall fishery were over four times more likely to be hooked in the mouth with circle hooks than with J-style hooks. Several target and bycatch species showed higher rates of survival at haulback with circle hooks, although only for dolphinfish in the fall fishery was this difference statistically significant. Our results suggest that the use of 0° offset circle hooks in the coastal pelagic longline fishery will increase the survival of bycatch species at haulback with minimal effects on the catches of target species.

Keywords: Pelagic longline; Bycatch; Circle hooks; Survival; Discard mortality

1. Introduction

Pelagic longline fishing gear is currently used throughout the world's oceans to commercially harvest swordfish *Xiphias gladius* and tunas *Thunnus* spp. Pelagic longline gear also interacts with non-target pelagic species, including istiophorid billfishes, sharks, sea turtles, and on occasion, marine mammals. Reducing the rate of interaction and mortality of non-target species has been identified as a fisheries management priority both domestically and internationally. In particular, interactions with billfishes by the pelagic longline fleet have created concern because of the depressed condition of Atlantic billfish stocks and the importance of these species to recreational anglers.

The fishing mortality on bycatch species resulting from pelagic longline fishing may be reduced by decreasing interaction rates and/or the number of animals dead at haulback. Recent attention has been given to circle hooks (a hook with the point turned perpendicularly back to the shank) as a means to reduce fisheries mortality. In contrast to J-style hooks, circle hooks tend to slide over soft tissue and rotate as the eye of the hook exits the mouth, frequently resulting in the hook catching in the jaw (Cooke and Suski, 2004; Trumble et al., 2002). Circle hooks have been used for years by commercial fisheries in the U.S. Pacific Northwest (IPHC, 1998) and are increasingly being used voluntarily in a number of U.S.

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marine recreational fisheries. Most research into the effects of hook type and survival has occurred in the recreational fishery where catch and release fishing practices are common. These studies have shown reduced rates of serious injury with circle hooks (Prince et al., 2002; Skomal et al., 2002; Malchoff et al., 2002) and increased rates of postrelease survival (Horodysky and Graves, 2005). In the pelagic longline fishery, a higher proportion of fishes caught in the mouth or jaw should result in less physical damage to the animal and presumably higher rates of survival at haulback and after release for bycatch species.

The effects of terminal gear changes in the pelagic longline fisheries have not been well studied. Falterman and Graves (2002) found that mortality at haulback of the longline was 31% for target and bycatch fishes caught on circle hooks and 42% for those caught on J-style hooks, although this difference was not statistically significant. Hoey (1996) observed a similar pattern in his review of the U.S. pelagic longline fleet records (mortality rate at haulback: 49% circle hook and 62% J-style hook; no significance noted). Yamaguchi (1989) hypothesized that differences in survival at haulback were related to hook location, in that jaw-hooking allowed the fishes to continue to swim while on the line. Berkeley and Edwards (1996) noted that fish caught on circle hooks, even those on the line for many hours, were generally alive at haulback. In the U.S. Atlantic longline fleet (which primarily used J-style hooks at the time), 80% of the billfish caught in 1998 were reported alive at haulback (Cramer, 2000). In contrast, less than 40% of the billfishes caught by the Venezuelan longline fleet (which also primarily used J-style hooks) were alive at haulback (Jackson and Farber, 1998), possibly an effect of the additional stress from the higher ambient water temperatures.

The use of circle hooks with pelagic longline gear has not been readily accepted by the fishery as an equally effective terminal gear type, and a large percentage of the international pelagic longline fishery in the Atlantic Ocean continues to use straight-shank or J-style hooks. Some vessels targeting tuna switched voluntarily to circle hooks following preliminary studies that suggested that this hook style may increase tuna catch rates (e.g., Hoey, 1996; Falterman and Graves, 2002). The International Commission for the Conservation of Atlantic Tunas (ICCAT) has encouraged the use of circle hooks in the Atlantic pelagic longline fisheries for several years. However, only the U.S. longline fleet is currently required to use circle hooks (69 F.R. 40733), a regulatory action precipitated by concerns over gear interactions with sea turtles, not the bycatch of pelagic fishes.

Little work has been conducted on comparisons of hook types on target catch and bycatch rates and mortality in the U.S. Atlantic pelagic longline fishery. Prior to the regulation mandating circle hook usage, and excepting the northern Gulf of Mexico yellowfin tuna fleet, the U.S. pelagic longline fleet historically used size 9/0 J-style hooks (Hoey and Moore, 1999). Berkeley and Edwards (1996) anecdotally observed a lower rate of mortality at haulback for the billfishes caught on circle hooks in the northern Gulf of Mexico. However, that study did not compare hook types per se, and the authors only noted this observation and suggested it as an avenue for future research. Hoey and Moore (1999) also suggested that a switch to circle hooks and dead bait by the yellowfin tuna-targeting vessels would result in an increase in tuna catch rates. More recently, a multi-year project with the U.S. Grand Banks pelagic longline fleet compared the efficiency of several hook types on catches of swordfish, bigeye tuna *Thunnus obesus*, and sea turtles. Circle hooks (size 18/0) baited with squid decreased swordfish catch rates, yet increased tuna catches compared with similarly baited size 9/0 J-style hooks (Watson et al., 2005). Circle hooks in that study also significantly reduced the number of loggerhead *Caretta caretta* and leatherback *Dermochelys coracea* sea turtle interactions.

It appears that circle hooks have promise for reducing bycatch mortality, but this potential has not been well quantified, especially for pelagic fishes. We undertook this study to assess the nature of the differences in catch rates and condition of target and non-target species caught with circle and J-style hooks in the western North Atlantic coastal pelagic longline fishery.

2. Materials and methods

The gear deployment configurations we used were standard for the U.S. Atlantic coastal pelagic longline fishery, with the only differences being the alternating hook types and the use of approximately 15 small temperature–depth recorders (TDRs) and 180 hook–time recorders (HTRs) per set. The choices of leader lengths, buoy drop lengths, leaded swivel weights, locations, lightstick color, and bait types were typical of the vessels in this fishery. The locations and seasons were chosen specifically because they are traditional fishing areas for the U.S. coastal pelagic longline fleet.

We conducted 85 sets on a commercial pelagic longline fishing vessel (F/V *Carol Ann*; ca. 16 m LOA) during two field seasons. The first (fall) season lasted from July to September 2003 and consisted of 39 sets in the mixed tuna and swordfish fishery along the mid-Atlantic continental shelf between Wilmington Canyon (offshore from Maryland) northward to Lydonia Canyon on the southwestern edge of Georges Bank, within the NOAA Fisheries Mid-Atlantic Bight (MAB) and Northeast Coastal (NEC) statistical areas. The second (spring) season lasted from January to April 2004 and consisted of 46 sets targeting swordfish in three southern locations: the Yucatan Channel (between Mexico and Cuba), the Windward Passage (between Haiti and Cuba), and the western Florida Straits around Key West, FL. These second areas are encompassed by the Gulf of Mexico (GOM) and Caribbean (CAR) statistical areas.

Four sections of pelagic longline gear were fished as part of normal commercial operations (Fig. 1). A section consisted

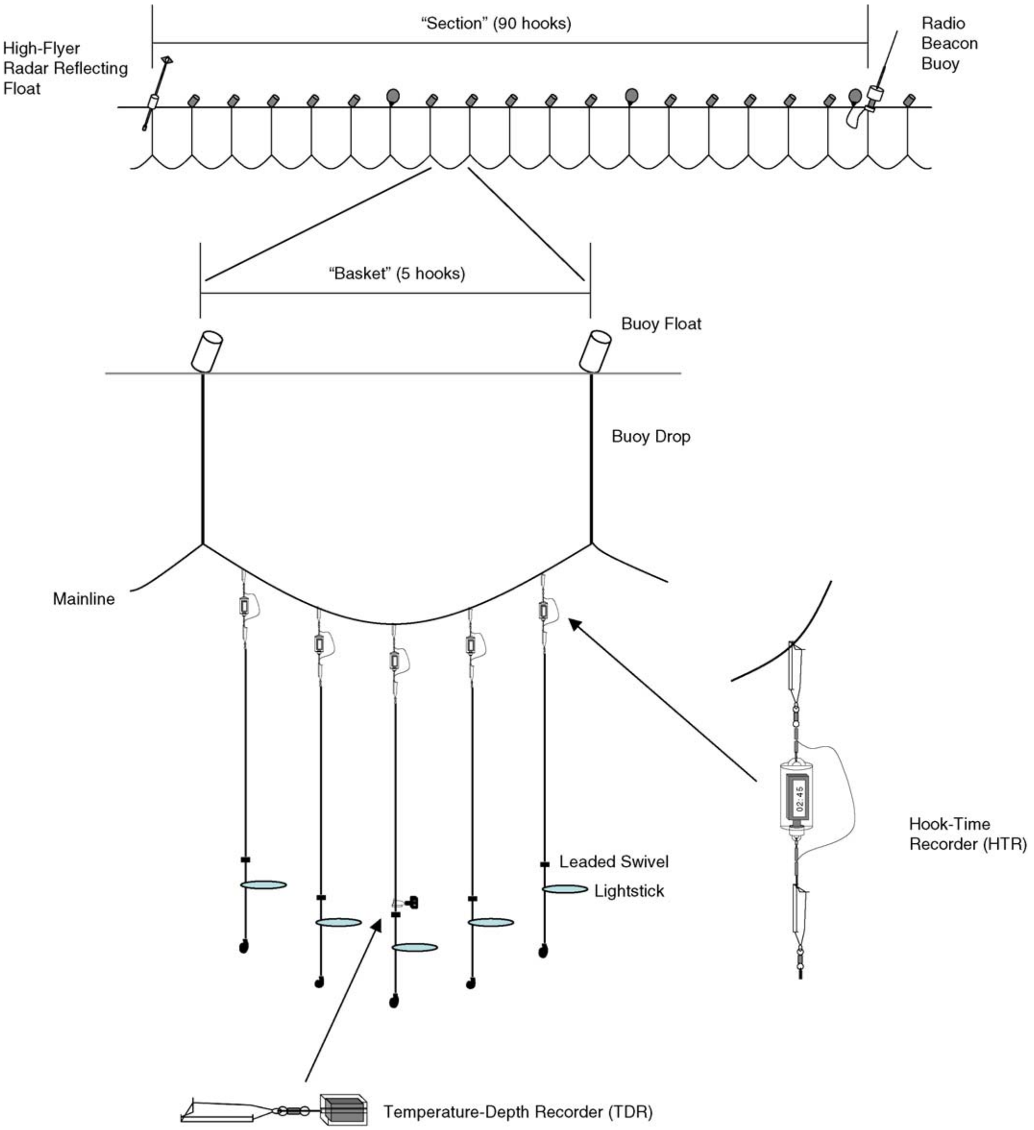

Fig. 1. Schematic diagram (not to scale) of coastal pelagic longline gear configuration used during 85 sets in the western North Atlantic, showing placement of hook–time recorders (HTRs) and temperature–depth recorders (TDRs). Lengths of buoy drops and leaders varied by season. For clarity, baits are not shown on hooks.

of 90 hooks and was separated by either a radar-reflecting high-flyer float or radio location buoy. Size 16/0, 0° offset circle (Mustad #39660ST or #39666DT) and 10° offset, size 9/0 J-style (Mustad #7698 or Eagle Claw #9016) hooks were alternated in each of the four sections. Each basket (the section of line between small buoy floats) contained five hooks to ensure alternating positions of each hook within the baskets along the mainline (i.e., one basket would have C–J–C–J–C and the next would have J–C–J–C–J). Leaders were stored in separate leader boxes by hook type and color-coded with plastic chafing gear at the junction of the clip and leader. Adjusting for different target species, individual leader lengths were 7.5 fathoms (ca. 13.7 m) in the fall fishery and 15 fathoms (ca. 27.4 m) in the spring, a standard practice within the fleet. Two buoy drop lengths were used in each set, alternating every 30 hooks, usually 5- and 2.5-fathom (ca. 9.1 m and 4.5 m, respectively) lengths in the fall and 10- and 12-fathom (ca. 18.3 m and 21.9 m, respectively) lengths in the spring. Squid *Illex* sp. were used in the fall fishery and Atlantic mackerel *Scomber scombrus* or a mixture of squid and mackerel in the spring fishery.

We recorded species, hook type, hooking location on the animal, disposition (alive or dead) at the time of haulback, buoy line length, and gangion number during haulback. Lengths of fish not retained (e.g., longfin mako sharks *Isurus paucus* and live istiophorid billfishes) were estimated, as were the lengths of any fish damaged by scavenging or the haulback process. Sharks, rays, and large fishes were released by cutting the leader as close to the animal as safely possible. Small fishes, such as snake mackerels *Gempylus serpens*, were generally hauled onto the deck and the hook recovered. Fish of sufficient length for legal retention were counted as "retained" even if damaged. Due to the difficulty of distinguishing among species without removal from the water, all carcharhinid sharks (other than the easily distinguished oceanic whitetip *Carcharhinus longimanus* and blue shark *Prionace glauca*) were recorded at the family level. Categories of hooking location were modified from Yamaguchi (1989) and include such descriptors as "corner," "lower jaw," and "upper jaw." However, the low number of individuals of some species required a collapse of the categories into "external" and "internal" designations: locations were considered "external" if the bend of the hook was visible when the mouth was open, i.e., the bend of the hook was not posterior to the esophageal sphincter of the animal, including hooking locations on the body ("foul hooked"). All other locations were considered "internal."

Time-at-hooking was assessed with electronic hook–time recorders (model HT600; Lindgren-Pitman, Inc., Pompano Beach, FL, USA). This HTR model is activated by approximately 7 lb of pull and records time of hooking for up to 24 h. The HTRs were manually attached during the setting operation between the individual leaders and the mainline on the first 180 hooks per set and examined at haulback for activation. HTR records of less than 2 min or greater than the duration of the set were omitted from subsequent analyses, as they were likely activated by the action of the gear. Data from activated HTRs were recorded along with the local time to determine the time that the animal was hooked. Activated HTRs without an attached animal or damage to the leaders were noted to provide an estimate of false activations, and it was also noted if a hooked animal did not activate the HTR. To further evaluate the time of hooking for animals with HTR records, local sunrise and sunset times were obtained from the Tides & Currents computer program (v. 2.00; Nautical Software, Inc., Portland, OR, USA).

Small temperature–depth recorders (DSTmilli model, 3 m resolution, Star-Oddi Corporation, Rekjavik, Iceland, and LTD_1100 model, 1.9 m resolution, Lotek Wireless, St. Johns, Newfoundland, Canada) were also deployed on each set and placed on the leaders approximately 4 m above the bait. Data from the TDR deployments were used to calculate maximum depths, as well as the length of time the gear was sinking after deployment or rising during haulback.

Catch rates were expressed as catch-per-unit-effort (CPUE) values of the number of individuals caught per 1000 hooks. Catches were broken down into individual species and the following species groups: "ALL SWO" for all swordfish, "RET SWO" for only retained (of legal size) swordfish, "ALL RET" for all retained fishes (including swordfish), "ALL TUNA" for all thunnid tunas, "ISTIO" for all istiophorid billfishes, and "UIC" for unidentified carcharhinid sharks.

Statistical tests were performed using SAS (v. 9.0; SAS Institute, Cary, NC, USA), and test results were considered significant at the 5% confidence level (i.e., $P < 0.05$) unless stated otherwise. Chi-square goodness-of-fit tests were used to compare catch rates within each seasonal fishery on each of the different buoy drop lengths. All remaining tests were performed only for species or species groups with >10 individuals. Differences in CPUE between circle hooks and J-style hooks for the species with >10 individuals were tested with paired *t*-tests after performing the $X' = \log(X + 1)$ transformation to conform to the assumption of normality (Zar, 1996). Because most species were not present across both seasons (precluding the use of an ANOVA analysis), multiple GLMs were performed on length frequency data for the three species most frequently caught and/or retained to assess potential size-selectivity for each hook type. Only measured lengths were included in length–frequency tests. The α-significance level of all tests was subject to the Bonferroni correction to account for the multiple testing of the non-independent datasets. Two-way analyses of variance tests (ANOVAs) were used to assess the relationship between lengths of time surviving and hook type, lengths of time surviving and individual length, and lengths of time surviving and hook location.

For the purposes of this study, fish that did not actively move in the water or on deck were conservatively considered "dead," as per Falterman and Graves (2002). The Cochran–Mantel–Haenszel chi-square test (CMH χ^2) was used to compare differences in survival at haulback for infrequently caught species due to the robust nature of the test to relatively low sample sizes, and also used to compare differences in hooking location between the two hook types. Odds ratios were used to calculate the relative increase of certain conditions (e.g., being dead at haulback on a J-style hook versus circle hook).

3. Results

3.1. Catch rates

We conducted 85 sets between July 2003 and April 2004, deploying 30,600 test hooks and 15,300 hook–timers. Sets were split between the fall fishery ($n = 39$) in the Mid-Atlantic Bight and Northeast Coastal statistical areas (MAB/NEC) and the spring fishery ($n = 46$) in the southern Gulf of Mexico and Caribbean areas (GOM/CAR). All gear was hauled in reverse order of set – i.e., the last section set out at night was the first to be retrieved in the morning – with the exception of two sets in 2003 that were hauled in the order they were set due to adverse weather conditions. Removing from consideration the two reversed sets, and eight sets in which the mainline parted and required a search for the gear, the shortest (the last hook in the fourth section of gear) and longest (first hook in the first section) soak times in the fall fishery were 13:01 h and 18:29 h, respectively. In the spring fishery, the shortest and longest soak times were 11:12 h and 17:23 h, respectively. Comparisons of both swordfish and overall catch rates between the two bait combinations in the spring GOM/CAR fishery showed that overall catch rates decreased significantly during all mackerel sets ($P = 0.034$). However, the GOM spring fishery targeted swordfish, and

Table 1
Catch composition and percent mortality at haulback by hook type for 10 most commonly caught fishes, separated by field season

Species	Percent composition (*n*)	Percent mortality	
		Circle hook	J-style hook
Season 1: fall 2003 (MAB/NEC)			
Yellowfin tuna *Thunnus albacares*	19.7 (121)	58.7	69.6
Pelagic stingray *Pteroplatytrygon violacea*	19.3 (119)	3.2	4.5
Swordfish *Xiphias gladius*	17.6 (108)	77.5	79.4
Dolphin *Coryphaena hippurus**	15.1 (93)	6.5	29.8
Blue shark *Prionace glauca*	10.1 (62)	7.4	22.8
Alepisaurus spp.	2.9 (18)	50.0	62.5
White marlin *Tetrapturus albidus*	2.8 (17)	40.0	33.3
Albacore *Thunnus alalunga*	2.4 (15)	83.3	100.0
Bigeye tuna *Thunnus obesus*	2.3 (14)	62.5	83.3
Unidentified carcharhinid shark	1.8 (11)	0.0	0.0
Season 2: spring 2004 (GOM/CAR)			
Swordfish *Xiphias gladius*	65.5 (559)	74.4	75.7
Unidentified carcharhinid shark	8.0 (69)	33.4	46.7
Escolar *Lepidocybium flavobrennum*	7.5 (64)	26.3	57.7
Alepisaurus spp.	2.7 (23)	50.0	86.7
Dolphin *Coryphaena hippurus*	2.7 (23)	7.7	10.0
Oilfish *Ruvettus pretiosus*	1.9 (16)	20.0	66.7
Great barracuda *Sphyraena barracuda*	1.8 (15)	16.7	100.0
Sailfish *Istiophorus platypterus*	1.6 (14)	14.3	42.8
Bigeye tuna *Thunnus obesus*	1.1 (9)	57.1	100.0
Snake mackerel *Gempylus serpens*	1.1 (9)	75.0	80.0

Numbers include both retained and discarded animals. Asterisk (*) indicates significant difference. Season 1—other species: shortfin mako shark *Isurus oxyrinchus* (7), tiger shark *Galeocerdo cuvier* (7), manta ray *Manta birostris* (6), ocean sunfish *Mola mola* (5), scalloped hammerhead shark *Sphyrna lewini* (3), snake mackerel *Gempylus serpens* (2), longfin mako shark *Isurus paucus* (2), blue marlin *Makaira nigricans* (1), *Cubiceps capensis* (1), sailfish *Istiophorus platypterus* (1), skipjack tuna *Katsuwomus pelamis* (1), and wahoo *Acanthocybium solanderi* (1). Season 2—other species: blackfin tuna *Thunnus atlanticus* (8), blue marlin *Makaira nigricans* (8), tiger shark *Galeocerdo cuvier* (6), ocean sunfish *Mola mola* (6), white marlin *Tetrapturus albidus* (4), yellowfin tuna *Thunnus albacares* (3), *Cubiceps capensis* (3), wahoo *Acanthocybium solanderi* (2), bigeye thresher shark *Alopias superciliosus* (2), oceanic whitetip shark *Carcharhinus longimanus* (2), albacore *Thunnus alalunga* (1), king mackerel *Scomberomorus cavalla* (1), longbill spearfish *Tetrapturus pfleugeri* (1), shortfin mako shark *Isurus oxyrinchus* (1), oceanic puffer *Lagocephalus lagocephalus* (1), pelagic stingray *Pteroplatytrygon violacea* (1), scalloped hammerhead shark *Sphyrna lewini* (1), and Atlantic cutlassfish *Trichiurus lepturus* (1).

there was not a significant difference in swordfish catch rates between bait types.

Catches are summarized for both seasons in Fig. 2 and Table 1. The targeted species in each fishery (nominally yellowfin tuna *Thunnus albacares* in the fall fishery and swordfish in the spring) was the most commonly caught, retained fish. The mixed-species MAB/NED fall fishery caught 615 fishes representing 22 species, with yellowfin tuna, pelagic stingray *Pteroplatytrygon violacea*, and swordfish comprising 56.6% of the catch. In contrast, sets targeting swordfish in the GOM/CAR spring fishery caught 853 fishes representing 29 species, with swordfish comprising 65.5% of the catch. Many fishes were damaged by scavenging while on the line, including 23 yellowfin tuna, 8 swordfish, 3 bigeye tuna, and 3 albacore *Thunnus alalunga* in 2003, and 25 swordfish, 1 blue marlin *Makaira nigricans*, 1 escolar *Lepidocybium flavobrunneum*, and 1 wahoo *Acanthocybium solanderi* in 2004. This represents a loss of 19% of the total yellowfin tuna caught in 2003 and 4.5% of total swordfish caught in 2004, comparable to the 4% of the catch by number reported damaged in the fishery by Hoey and Moore (1999).

Catch rates varied between the two field seasons and among species and species groups. The fall season had an overall CPUE of 43.8 (per 1000 hooks) for all species, with a significantly lower catch rate on circle hooks than on J-style hooks (38.0 versus 49.5; $P = 0.027$), although 19.3% of the total catch was pelagic stingray *P. violacea*, a bycatch species (Fig. 3). Comparing only retained species, the catch rate differences between hook types were not statistically significant. Yellowfin tuna in the fall fishery had the highest overall CPUE for an individual species (8.6 per 1000 hooks), and circle hooks had a significantly higher CPUE (10.7) than J-style hooks (6.4) for this species (t-value = 2.47, $P = 0.018$). Of all the species and species groups, only the pelagic stingray showed a significantly higher catch rate on J-style hooks (12.5 versus 4.4 on circle hooks; $P < 0.0001$). The spring season CPUE for all species (51.5 fish per 1000 hooks) was higher than that of the fall (43.8), but this difference was not significant. Swordfish had the highest overall CPUE during this season of any species (33.7 per 1000 hooks; including both retained and released undersized animals). No species or species group in the spring season had a statistically significant catch rate difference between the hook types.

Chi-square goodness-of-fit tests were used to evaluate the hypothesis that catch was constant across leader number (i.e., expected values = 20% of the catch at each of the five lead-

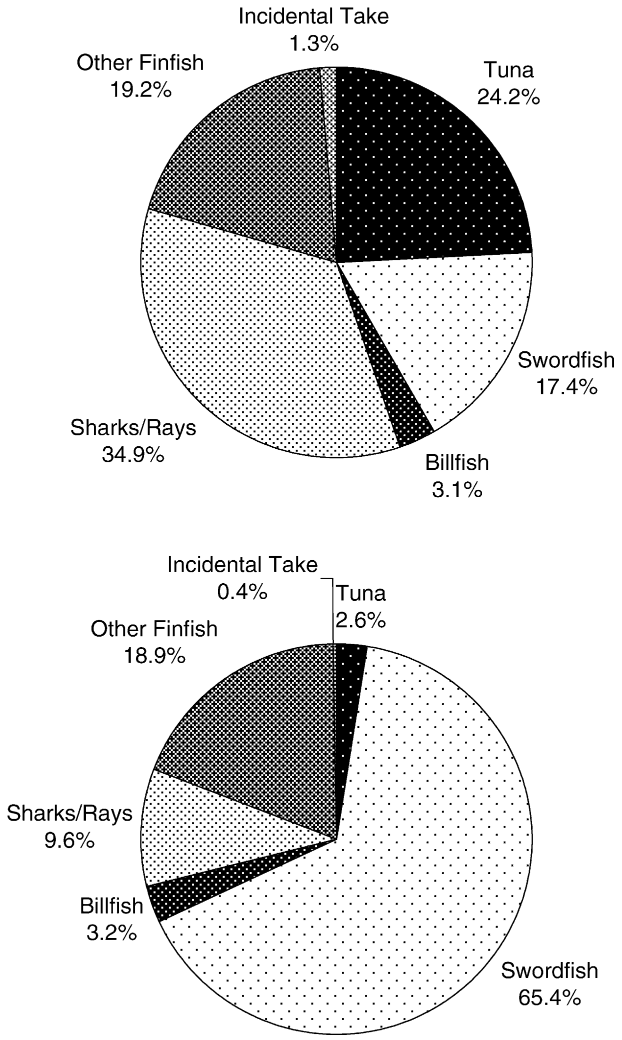

Fig. 2. Species catch composition by season for pelagic longline sets in the Mid-Atlantic Bight and Northeast Coastal NOAA Fisheries statistical areas (fall fishery; upper chart) and the Gulf of Mexico and Caribbean (spring fishery; lower chart). "Incidental take" includes all turtles and marine mammals, while the "tuna" category includes only *Thunnus* spp.

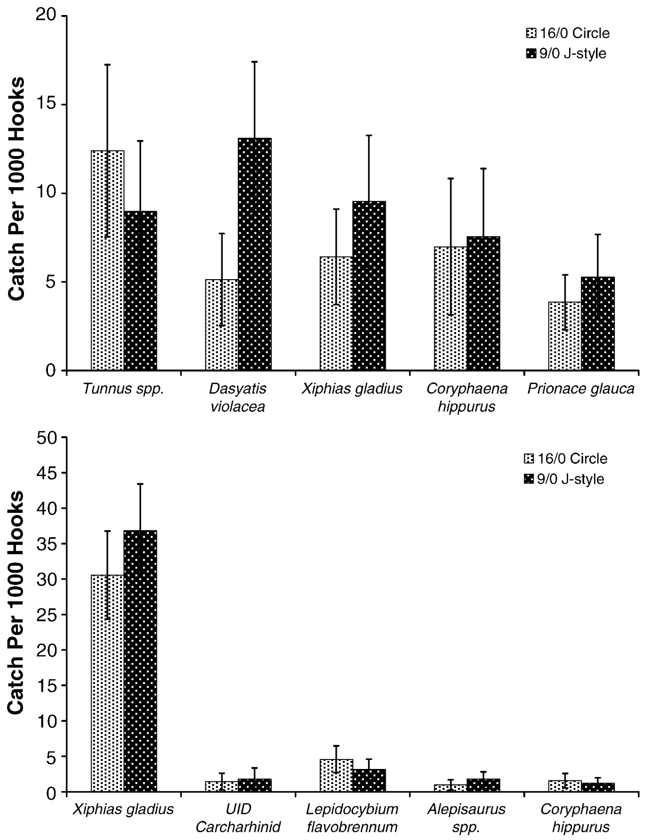

Fig. 3. Comparisons of CPUE (catch per 1000 hooks) among size 16/0, 0° offset circle hooks and size 9/0, 10° offset J-style hooks for pelagic longline sets in the Mid-Atlantic Bight and Northeast Coastal NOAA Fisheries statistical areas (fall fishery; top) and the Gulf of Mexico and Caribbean (spring fishery; bottom).

ers). In the fall fishery, only dolphinfish *Coryphaena hippurus* showed a significant preference for the shallower hooks next to the buoy floats ($n = 93$; $\chi^2 = 10.82$, $P = 0.029$). In the spring fishery, both retained swordfish ($\chi^2 = 52.5422$, $P < 0.0001$) and "UIC" (sharks; $\chi^2 = 10.2143$, $P = 0.037$) showed significant preferences for the deeper hooks (i.e., hook numbers 2–4). No other species or species group in the fall or

Table 2
Results of Bonferroni-corrected *t*-tests (significance at $P = 0.05/5$, so that $P_{adj} = 0.01$) on length frequencies by hook type, separated by field season

Species	Mean length ± S.D.		*t*-Value ($P > \|t\|$)
	Circle hook	J-style hook	
Season 1: summer/fall 2003			
Yellowfin tuna *Thunnus albacares* ($n = 90$)	116.1 ± 9.24	111.3 ± 6.88	2.69 ($P = 0.009$)*
Swordfish *Xiphias gladius* ($n = 62$)	128.0 ± 23.84	140.8 ± 30.97	−1.73 ($P = 0.089$)
Dolphinfish *Coryphaena hippurus* ($n = 88$)	85.7 ± 18.81	82.7 ± 19.60	0.73 ($P = 0.466$)
Season 2: winter/spring 2004			
Swordfish *Xiphias gladius* ($n = 471$)	145.9 ± 29.95	141.63 ± 29.88	1.53 ($P = 0.126$)
Escolar *Lepidocybium flavobrennum* ($n = 55$)	89.8 ± 28.16	92.39 ± 16.18	−0.42 ($P = 0.674$)†
Dolphinfish *Coryphaena hippurus* ($n = 23$)	98.5 ± 13.68	85.6 ± 6.52	2.98 ($P = 0.008$)*,†

Note that numbers include both retained and discarded animals. Mean lengths given in centimeters.

* Significant at $P < 0.01$ level.

† Satterthwaite *t*-test for unequal variances.

spring fisheries showed significant differences, indicating fairly equal catch rates across all hook positions within baskets.

Chi-square goodness-of-fit tests were also used to evaluate whether catch rates were equal among buoy drop lengths per season. In the fall fishery, only yellowfin tuna showed a significant preference for a particular buoy line length, in this case for the shorter 2.5-fathom lines ($n = 121$; $\chi^2 = 12.0839$, $P = 0.002$).

To assess possible relationships between individual size and hook type, length–frequencies were separately tested within and between seasons for hook type (Table 2). Subject to the Bonferroni correction (significance at $P = 0.05/5$, so that $P_{\text{adj}} = 0.01$), only yellowfin tuna in the fall (Fig. 4A) were significantly longer on circle hooks ($n = 90$; $P = 0.009$; mean sizes: 116 cm (±9) FL circle and 111 cm (±7) FL J-style). In the spring, only dolphinfish (Fig. 4B) showed a significant length–frequency difference between hook types ($n = 23$; $P = 0.0081$; mean sizes: 98 cm (±14) FL circle and 86 cm (±6) FL J-style). No similar effect of hook types was seen with lengths of either swordfish or escolar, the two other retained species caught in sufficiently large numbers for robust statistical analyses.

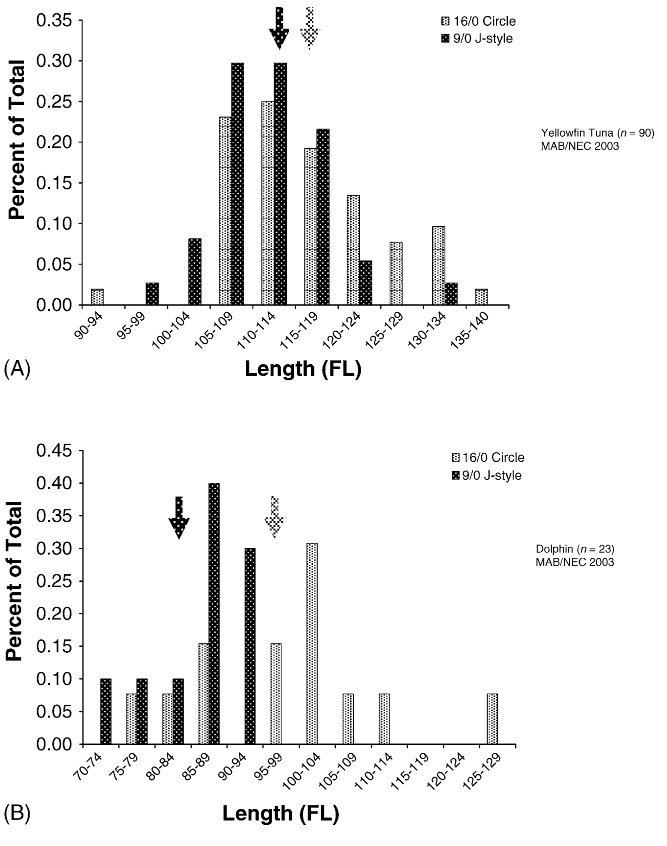

Fig. 4. Length–frequency distributions for (A) yellowfin tuna (fall fishery) and (B) dolphin (spring fishery) caught on size 16/0, 0° offset circle hooks and size 9/0, 10° offset J-style hooks. For both species, individuals caught on circle hooks were significantly larger than those caught on J-style hooks. Arrows point to the bin containing the mean length for each hook type.

3.2. Mortality at haulback and hooking location

Mortality rates at haulback varied considerably among species and between seasons (Table 1). Within seasons, significantly fewer escolar in the spring fishery were dead at haulback on circle hooks versus J-style hooks (26% and 58%, respectively; $\chi^2 = 6.285$, $P = 0.01$). Similarly, dolphinfish were significantly more likely to be alive on circle hooks ($\chi^2 = 8.333$, $P < 0.004$), and 5.8 times more likely to be dead at haulback in the fall fishery when caught with J-style hooks. Mortality at haulback was not significantly different for any other species or species group during either seasonal fishery, including the putative target species. Smaller species, such as the mesopelagic lancetfishes *Alepisaurus* spp. and snake mackerel *G. serpens*, were frequently dismembered during the haulback process, preventing accurate evaluations of mortality related to hook type.

Hooking locations varied widely between hook types and fishing seasons, and among species (Fig. 5). For example, circle hooks were lodged in the jaw in 82% of the yellowfin tuna, with most of those hooked in the corner of the jaw (68%). The istiophorid billfishes were predominantly (92.8%) hooked in

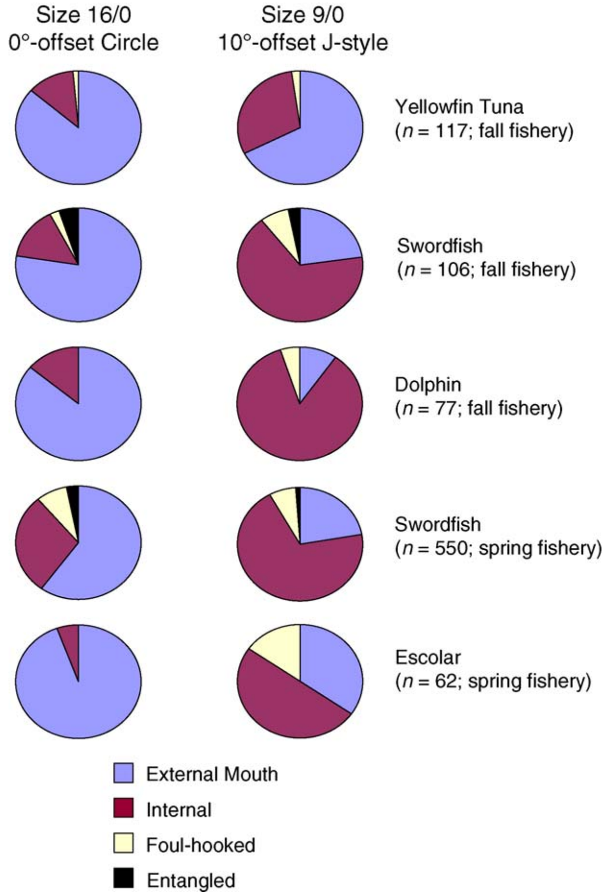

Fig. 5. Hooking location by species for pelagic longline sets in the Mid-Atlantic Bight and Northeast Coastal NOAA Fisheries statistical areas (fall fishery) and the Gulf of Mexico and Caribbean statistical areas (spring fishery).

the jaw with both hook types. The high numbers of swordfish caught in both fisheries allowed for more detailed comparisons of hook location analyses. Specifically, circle hooks lodged in the jaw of swordfish 74% of the time in the fall fishery, while only 54% were hooked in this location in the spring fishery. In the spring fishery, more swordfish swallowed the circle hook (3% in fall versus 11% in spring) and were foul-hooked (3% in fall versus 11% in spring). For swordfish caught on J-style hooks, the hooks lodged in the palate 44% of the time in fall and 46% in spring, and were swallowed 23% of the time in fall and 24% of the time in spring.

Most species were caught in insufficient quantities in both seasons to allow meaningful comparisons of precise hook location by hook type, requiring the collapse of the hooking location categories into "external" and "internal." During the fall season, yellowfin tuna, swordfish, and dolphinfish were all significantly more likely to be hooked externally with circle hooks ($P = 0.005$, <0.0001, and <0.0001, respectively). Yellowfin tuna in the fall season were over four times as likely to be externally hooked when caught by circle hooks (odds ratio: 4.02). Circle hooks were more likely to hook both swordfish and escolar externally than J-style hooks ($P < 0.0001$) during the spring season. Several species did not show a clear trend for specific hooking locations between hook types. Pelagic rays, for example, were caught in the mouth 93% of the time with circle hooks and 84% with J-style hooks, although all eight foul-hooked animals were caught on J-style hooks. Lancetfishes were caught during the spring GOM/CAR season in the jaw 88% of the time with circle hooks and 94% with J-style hooks. In the fall MAB/NEC fishery, blue sharks were caught 26% of the time internally on both hook types, but all three foul-hooked or entangled sharks were caught on J-style hooks.

Total bycatch of protected species (nine combined marine mammals and sea turtles) was minimal in this study, comprising only 0.6% of the total catch, and all protected species were released alive following removal of the attached fishing gear (Table 3). Five of the turtles were loggerheads, all caught with J-style hooks hooked in either the roof/throat ($n = 4$) or in the lower jaw ($n = 1$). The remaining four turtles were leatherbacks and were foul-hooked in the front flipper, three by J-style hooks and one with a circle hook. Both marine mammals were pilot whales *Globicephala* spp. that were entangled with the mainline on their tail stocks, just forward of the flukes.

3.3. Time of capture

A total of 599 activated HTRs were recovered with fish (or identifiable fish parts) on the leader, representing 23 different species or species groups (Table 4). Yellowfin tuna in the fall fishery and swordfish in the spring fishery showed significantly higher mortality rates with increased time on the hook ($P < 0.0001$). Only yellowfin tuna exhibited a significantly higher survival rate over time with circle hooks ($P = 0.0004$). However, few species were caught frequently enough on both hook types and HTRs to permit this analysis. No species or species group exhibited significantly longer survival time as a function of individual size. Only yellowfin tuna in the fall fishery and swordfish in the spring fishery were caught in sufficient numbers in both hooking locations (internal or external) and with HTR records to assess a relationship between survival time and hooking location—neither species exhibited a significant relationship.

Time at hooking varied among species. Almost all swordfish were hooked at night (99%) with only four hooked during daylight periods in the fall season. All of the bigeye tuna caught on leaders with HTRs ($n = 17$) were caught during the night, as were all but one blackfin tuna *Thunnus atlanticus* ($n = 7$). Yellowfin tuna showed no clear preference between daylight (57%) and nighttime (43%) feeding. Only 1 of 28 escolar was caught during daylight, and this animal was hooked just prior to local sunrise. Blue sharks were more often hooked at night (85%). Dolphinfish with HTR records were almost all caught during daylight (95%). The two individuals hooked at night were caught within 45 min of local sunrise. All but 2 of the 21 billfish with known capture times were caught during daylight hours. The two exceptions were a sailfish *Istiophorus platypterus* caught less than an hour

Table 3
Catch composition and details for protected species interactions

Date	Set	Area	Species	Hook type	Hooking location
4 August 2003	7	NEC	Loggerhead turtle	J-style	Roof/throat
9 August 2003	11	NEC	Loggerhead turtle	J-style	Roof/throat
7 September 2003	23	MAB	Shortfin pilot whale	N/A	Entangled in mainline
14 September 2003	30	MAB	Shortfin pilot whale	N/A	Entangled in mainline
8 October 2003	37	MAB	Leatherback turtle	J-style	Foul-hooked
9 October 2003	38	MAB	Leatherback turtle	J-style	Foul-hooked
9 October 2003	38	MAB	Loggerhead turtle	J-style	Roof/throat
10 October 2003	39	MAB	Loggerhead turtle	J-style	Roof/throat
10 February 2004	52	GOM	Loggerhead turtle	J-style	Lower jaw
27 February 2004	59	CAR	Leatherback turtle	Circle	Foul-hooked
9 April 2004	77	GOM	Leatherback turtle	J-style	Foul-hooked

All animals were released alive. Area abbreviations for NOAA Fisheries statistical areas: NEC, Northeast Coastal; MAB, Mid-Atlantic Bight; GOM. Gulf of Mexico; CAR, Caribbean.

Table 4
Summary of time on line (hours:minutes) for major species, with sample size (*n*) and standard deviation in parentheses

Species	Year	Circle live	Circle dead	J-style live	J-style dead
Blue shark *Prionace glauca*	2003	12:44 (17; ±4:21)	11:47 (2; ±6:04)	11:13 (15; ±4:29)	14:33 (5; ±0:23)
Dolphinfish *Coryphaena hippurus*	2003	2:24 (16; ±2:08)	16:06 (1; n/a)	3:34 (11; ±2:05)	9:24 (3; ±5:31)
	2004	0:32 (2; ±0:09)	10:41 (1; n/a)	0:18 (2; ±0:06)	[None]
Escolar *Lepidocybium flavobrunneum*	2004	8:30 (12; ±2:57)	8:40 (6; ±4:09)	9:22 (4; ±0:24)	13:43 (6; ±4:02)
Swordfish *Xiphias gladius*	2003*	9:07 (5; ±4:17)	13:28 (18; ±2:56)	7:29 (2; ±2:12)	12:36 (28; ±3:40)
	2004	8:28 (31; ±3:52)	10:12 (92; ±3:30)	6:59 (30; ±3:23)	9:48 (110; ± 3:40)
Unidentified carcharhinid shark	2003	4:11 (2; ±3:33)	[None]	8:39 (3; ±2:43)	[None]
	2004	4:33 (3; ±1:10)	[None]	7:08 (5; ±5:01)	9:33 (4; ±5:16)
Yellowfin tuna *Thunnus albacares*	2003*	6:21 (15; ±5:46)	14:05 (19; ±5:56)	5:18 (7; ±3:02)	14:01 (14; ±5:02)
	2004	[None]	2:36 (1; n/a)	[None]	10:05 (1; n/a)

Numbers include both retained and discarded animals. Only swordfish and yellowfin tuna in 2003 were significantly more likely to be dead at haulback with an increased lengths of time on the line: an asterisk (*) indicates significance at the $P<0.0001$ level. Other species caught on HTRs: blackfin tuna *Thunnus atlanticus* (8), blue marlin *Makaira nigricans* (8), sailfish *Istiophorus platypterus* (8), tiger shark *Galeocerdo cuvier* (6), ocean sunfish *Mola mola* (6), white marlin *Tetrapturus albidus* (4), *Cubiceps capensis* (3), wahoo *Acanthocybium solanderi* (2), bigeye thresher shark *Alopias superciliosus* (2), oceanic whitetip shark *Carcharhinus longimanus* (2), albacore *Thunnus alalunga* (1), king mackerel *Scomberomorus cavalla* (1), longbill spearfish *Tetrapturus pfleugeri* (1), shortfin mako shark *Isurus oxyrinchus* (1), oceanic puffer *Lagocephalus lagocephalus* (1), pelagic stingray *Pteroplatytrygon violacea* (1), scalloped hammerhead shark *Sphyrna lewini* (1), and Atlantic cutlassfish *Trichiurus lepturus* (1).

prior to local sunrise during nautical twilight, and a large-sized blue marlin (estimated weight 250 kg) caught at 12:01 a.m. local time on a clear night.

Body size of the individual fish clearly affected the activation rates for HTRs. We caught 338 swordfish on HTRs over both seasons, and only 15 HTRs (4%) failed to activate (8 of these 15 inactivation events were juvenile swordfish under 100 cm lower jaw-fork length). HTRs were also attached to leaders catching 25 istiophorid billfishes combined during both seasons, only 1 of which failed to activate. Thunnid tunas also had a high rate of HTR activation (98% overall). However, several smaller species had extremely low rates of HTR activation, presumably because their small body size did not enable them to generate sufficient force to activate the HTR mechanism. These included alepisaurid lancetfish (17%) and snake mackerel, which had HTR activation rates at haulback of almost 0%. Pelagic stingrays also had very low rates of HTR activation (12%) regardless of individual size. Discounting small animals (<5 kg approximate weight) and pelagic stingrays, only 25 HTRs failed to activate in 2003 and 30 in 2004. Over both field seasons, 173 HTRs (1.1% of those activated) were recovered without a hooked animal or damage to the bait or leader.

TDR data indicate that most gangions reached fishing depth approximately 15 min after deployment, and baits were generally retrieved from this depth during haulback in approximately 15 min. Analysis of these TDR data in conjunction with the time-at-hooking information revealed that very few animals were caught during set out or haulback of the gear. Dolphinfish were a notable exception to this pattern, with 6 of 34 fish in the fall, and 3 of 5 fish in the spring, caught during set out or haulback. Mean maximum depths (depth of middle hook in basket) of the gear were 20.3 m (S.D. ±13.1 m) for a 2.5 fathoms buoy drop and 23.8 m (S.D. ±10.2 m) for a 5 fathoms buoy drop in the fall, and 52 m (S.D. ±21.7 m) for a 10 fathoms drop and 54 m (S.D. ±22.9 m) for a 12 fathoms drop in the spring. Leaders with TDRs attached caught a total of 31 fish (8% of TDR deployments) during the fall and spring fisheries.

4. Discussion

4.1. Catch rate comparison

We found few significant differences in catch rates of target or bycatch species between size 16/0, 0°-offset circle hooks and size 9/0, 10°-offset J-style hooks. Yellowfin tuna exhibited significantly higher catch rates with circle hooks in the fall fishery, mirroring previous studies comparing catch rates among hook types. In his review of the Gulf of Mexico pelagic longline fishery, which primarily targeted yellowfin tuna, Hoey (1996) reported that vessels caught 32.9 fish per set using circle hooks and only 27.2 fish per set using J-style hooks (122 and 75 sets, respectively). Falterman and Graves (2002) found a significant increase in CPUE for circle hooks relative to J-style hooks for both yellowfin tuna (mean CPUEs 33 and 1.3 per 1000 fish, respectively) and a composite "all fishes" category (mean CPUEs 50.5 and 23 per 1000 fish, respectively), although the low number of fish caught overall in their study prevented comparisons across other species. Although not significant, escolar and dolphinfish also had higher catch rates on circle hooks in the spring GOM/CAR swordfish fishery. It is worth noting that both Hoey (1996) and Falterman and Graves (2002) observed fisheries using predominantly live fishes as bait, rather than the frozen squid and/or mackerel used in our study. Falterman and Graves (2002) also used a smaller J-style hook (size 7/0 versus the size 9/0 in this study), as well as offset size 14/0 and 16/0 circle hooks. Varying hook sizes and configuration may affect catch rates through as-yet unquantified gape size or other morphological feeding limitations among various species groups. For example, smaller hooks caught more sea bream *Pagellus* spp. than larger hooks in a study by Erzini et al. (1998), and a relationship between hook size and size selectivity was seen with circle hooks and freshwater bluegill *Lepomis macrochirus* (Cooke et al., 2005). However, catch rates for serranid groupers were unaffected by hook size (Bacheler and Buchel, 2004). By using the two hook sizes and shapes common in the U.S. pelagic longline fishery, this study attempted to minimize possible confounding factors.

4.2. Mortality at haulback and hooking location

There were clear differences in survival of fishes caught on the two hook types used in this study. The overall lower rate of internal gut hooking we observed with circle hooks is consistent with the findings of prior studies on serranid groupers (Bacheler and Buchel, 2004), striped marlin *Tetrapturus audax* (Domeier et al., 2003), and white marlin *T. albidus* (Horodysky and Graves, 2005). Our results demonstrated that 88% of all yellowfin tuna caught in the MAB/NEC fall fishery were caught in the jaw by circle hooks, comparable to the results seen by Skomal et al. (2002) in which 95% of all juvenile bluefin tuna *Thunnus thynnus* caught on circle hooks in a recreational fishery were caught in the jaw. In conjunction with the HTR data showing that at least one species has longer survival times after being caught on circle hooks, the results of this study suggest that the use of circle hooks will result in lower mortality rates at haulback of target and non-target species.

As evidenced in this and previous pelagic longline studies, hooks often lodge in locations other than the jaw or gut. Falterman and Graves (2002) reported that gut-, foul-, and roof-hooking events were seen with J-style hooks, but not circle hooks, in the Venezuelan pelagic longline fishery. A total of 19 swordfish in this study were hooked in the bill, primarily with circle hooks, and more than 5% of all swordfish caught during the fall fishery were hooked in the bill or entangled with the gangion. Stillwell and Kohler (1985) noted that many of the squid and mesopelagic fishes in swordfish gut contents showed evidence of decapitation or slashing. This feeding behavior may explain the relatively high incidence of bill hookings. We also observed several fishes in which the point of the hook exited the eye or eye socket. Of the animals hooked through the eye in this study, eight were hooked with circle hooks and nine with J-style hooks. The large circle hook (size 16/0) used in this commercial gear study may increase the probability of hooks exiting through the eye socket. Skomal et al. (2002) reported that 3 of the 101 juvenile bluefin tuna landed in their study had eye damage resulting from hooks exiting in this location, and Horodysky and Graves (2005) only had 1 of 40 white marlin caught through the eye socket with recreational fishing gear and smaller, size 8/0 circle hooks.

4.3. Time of feeding

This study observed several patterns of feeding times among species, and some clearly demonstrated a preference for day or night feeding. Swordfish caught on hook timers were either hooked during dark or nautical twilight. No difference in the times of feeding at night was observed between under-sized (<120 cm LJFL) and legally retainable swordfish. All of the escolar were also caught at night or nautical twilight. Extremely active and presumably feeding bigeye tuna have been caught during daylight hours on other pelagic longline sets (D. Kerstetter, personal observation), although 92.8% of the bigeye tuna caught on HTRs in this study were caught during nighttime periods. In contrast, 97.8% of dolphinfish caught during both seasons were caught during daylight or nautical twilight.

Other species' feeding patterns were more varied, including the other tunas and billfishes. Yellowfin tuna and albacore demonstrated no preferential time of feeding. The billfishes fed primarily during the daylight and crepuscular hours; only one billfish was caught at night. This blue marlin was caught at approximately midnight on a clear night with moonlight, where visual feeding strategies may have been possible. The apparent preference for billfish to feed during daylight hours might suggest for more selective setting strategy to reduce billfish bycatch for the gear, especially with swordfish-targeting vessels. However, the demonstrated feeding of billfish during the sunrise period, when swordfish vessels usually haul back the gear, may preclude this preference as a bycatch reduction technique, unless the gear retrieval is completed by daybreak.

We found that very few animals were hooked during either setting or hauling of the gear. Only 19 fish total were caught within 30 min of the leader reaching the surface at haulback, including 9 dolphinfish and 3 billfish (2 blue marlin and 1 sailfish). Actively moving baits presumably are more attractive to fish, causing some to hypothesize that many fish are caught during haulback of the gear. TDRs deployed in this study found that many leaders experienced vertical movement during the time that the baits were presumed to have settled at depth, a finding consistent with Berkeley and Edwards (1996). However, these same TDR records clearly showed the movements of the hooks associated with set and haulback. Boggs (1992) indicated that 88% of bigeye and yellowfin tuna were caught when the gear was assumed to have settled to the target depths; however, a substantial proportion of striped marlin, shortbill spearfish *Tetrapturus angiorostris*, and dolphinfish were caught during setting or hauling. In contrast, Berkeley and Edwards (1996) found that a high proportion of yellowfin tuna were hooked during haulback. Although Boggs (1992) indicated that large percentages of some species caught in the Hawaii fishery were hooked during the set or haul of the gear, the much deeper depths fished in the Hawaii study also meant that the hooks were moving for longer periods of time and through additional water layers. The shallower depths and shorter gear used in the U.S.

coastal longline fishery on the Atlantic coast may therefore have lower catch rates of billfishes and dolphinfish than vessels fishing at deeper depths with longer gear for bigeye tuna in waters with a deeper mixed layer.

We found that mortality at haulback for yellowfin tuna was significantly related to the time on the hook, and several different species caught on leaders with TDRs exhibited vertical movement for several hours after hooking. For obligate ram-ventilating fishes such as the scombrids, the effective constrained swimming area resulting from capture on the line may prevent adequate respiration, translating into higher observed mortality rates at haulback. Several bigeye and yellowfin tuna survived after hooking for over 12 h, and although not a significant relationship, those hooked in the jaw tended to survive for longer periods of time. One medium-sized blue marlin (estimated weight 115 kg) was caught in 2004 with a circle hook in the corner of the jaw and was still alive at haulback over 14 h later. Boggs (1992) noted a high survival rate for striped marlin and bigeye tuna, some even after 6 h on the line. Berkeley and Edwards (1996) also noted that approximately half of the blue and white marlin hooked on the line for 5 h or more were alive at haulback. Many escolar, even those under 100 cm FL, were alive at haulback despite being on the line for over 7 h. Clearly, pelagic fishes can survive being hooked on the longline gear for extended periods, especially if hooked in the jaw. The survivability of fish caught on pelagic longline gear is therefore likely a combination of several factors, including hooking location (a function of hook type) and time on the line.

4.4. Management and conservation implications

Our results demonstrate that the use of 0° offset, size 16/0 circle hooks in the U.S. coastal pelagic longline fishery can reduce mortality at haulback for a suite of bycatch fishes without significantly affecting catch rates of commercially important species. In some situations, the use of circle hooks may even increase the catch of target species, such as yellowfin tuna. Circle hooks are more likely to hook animals externally rather the internally, and fishes caught on circle hooks exhibited longer survival time on the line. This longer survival time with circle hooks may also allow a higher percentage of undersized swordfish and istiophorid billfishes to be released alive than those animals caught with J-style hooks and increase ex-vessel revenue by resulting in a higher quality product.

The release of live, longline-caught bycatch species could promote the recovery of depleted stocks by reducing fishing mortality. Many pelagic fishes demonstrated survival in this study for long periods of time after capture, especially when hooked in certain locations, such as the jaw. We found that several pelagic fishes, including the billfishes, are hooked more frequently externally with circle hooks than the traditional J-style hooks, which is consistent with trends observed in several other studies of both recreational and commercial fisheries.

The results of our study showed that catch rates for targeted species may not be greatly affected by the mandatory change to circle hooks in the U.S. pelagic longline fishery, and that both target and non-target species caught by circle hooks may remain alive longer after capture. However, we only examined two fishing areas, the fall mixed fishery and the spring swordfish directed fishery. Results from other areas and targeted species, such as the northern Gulf of Mexico yellowfin tuna fishery, may differ. Our results suggest that the use of circle hooks will not prevent the catch of sea turtles; several were caught in this study with both hook types. Circle hooks will also not prevent the capture of billfishes, although they may increase the rate of survival at haulback for these fishes and thereby reduce overall fishing mortality. There may be additional benefits to the coastal pelagic longline fishery from the mandated switch to circle hooks. For example, the circle hooks in this study caught far fewer pelagic rays, a common bycatch species in the MAB/NEC areas. By decreasing the catch of some nuisance or non-market bycatch species, the use of circle hooks may save both crew time and overall vessel trip expenses such as those involved in the replacement of lost hooks. The conservation benefits and minor costs of circle hook use seen in this study of the U.S. domestic fishery should facilitate the exportation of this terminal gear type to the international longline fleets through international fisheries management organizations.

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