CSIRO PUBLISHING

www.publish.csiro.au/journals/mfr *Marine and Freshwater Research*, 2003, **54**, 435–445

Mortality rate of striped marlin (*Tetrapturus audax*) caught with recreational tackle

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Abstract. A project was initiated in the autumn of 2000 to document the mortality of striped marlin caught on recreational fishing tackle, with a follow-up study conducted in autumn of 2001. Fish were caught using typical recreational fishing methods and 80 pop-up satellite archival tags were deployed with new software and mechanical release mechanisms that allowed tags to detach and transmit early if the fish died. The first year study was also designed to compare the effectiveness and associated mortality of circle hooks versus J-hooks, while the second year study compared offset and non-offset circle hooks. All fish were caught on live bait. Circle hooks were found to be equally effective in hooking and landing striped marlin and far less likely to cause serious bleeding or become lodged in areas other than the mouth. Non-offset and 5° offset circle hooks had very similar performance. Depth and temperature records allowed us to determine the fate of individual marlin following release. In total, 16 of 61 fish died (mortality rate of 26.2%), all within 5 days of release (mean 1.5 days). Injury was a clear predictor of mortality; 100% of fish that were bleeding from the gill cavity died, 63% of fish hooked deep died, and 9% of those released in good condition died.

Extra keywords: angler, circle hook, PAT tags.

Introduction

On the west coast of North America, striped marlin are the basis of a large recreational fishery that, particularly in Baja California Sur, Mexico, is an important part of the economy (Squire and Au 1990). Over the years, tag and release of large sport fish, particularly billfish, has been strongly encouraged as a conservation measure. Conventional tagging of all marlin species has resulted in very low return rates (<1–2%) (Mather *et al.* 1974; Squire and Nielson 1983; Squire 1987; Bayley and Prince 1994), although this may be associated with tag shedding or non-reporting; high post-release mortality may also be a factor. Given the propensity to encourage catch and release as a conservation measure, it is important to examine mortality associated with recreational fishing and develop methods to reduce it.

Quantifying mortality is also critical for interpreting the fate of billfish released from commercial gear. Striped marlin are both targeted and caught incidentally on longline and drift gill-net gear in the eastern Pacific. It has been suggested that this longline activity may negatively impact nearby recreational striped marlin catch rates (Squire and Au 1990). Although not within the scope of this study, methods developed from this work could be applied to studies of commercial fishing mortality.

Acoustic telemetry, where individual fish are tracked for periods of hours to days, has been used to monitor billfish behaviour following release (Carey and Robison 1981; Holland *et al.* 1990; Holts and Bedford 1990; Block 1992*a*, 1992*b*; Brill *et al.* 1993; Pepperell and Davis 1999). However, with the exception of Pepperell and Davis (1999), these studies generally focused on short-term movement, behaviour and physiology of the fish, and therefore care was taken to select apparently healthy individuals while injured or overly stressed animals were purposely released without tagging. Mortality rates for billfish tagged with acoustic tags range from 0 to 50% depending on the study (summarized in Pepperell and Davis 1999). The advent of the pop-up archival transmitting (PAT) tag (Lutcavage *et al.* 2000; Block *et al.* 2001; Boustany *et al.* 2002) has provided a new tool to examine the fate of released fish. Graves *et al.* (2002) made the first attempt at measuring post-release mortality using PAT tags by deploying nine tags on blue marlin caught with recreational tackle. Although successful, their study was hampered by a limited sample size and less sophisticated tags. Until recently there have been no mechanisms in place to mitigate problems associated with the premature release of the tag or fish mortality. When a tag detached early, it would float on the surface until the pre-programmed release/transmission date was reached. Consequently, tags were vulnerable to washing ashore, being damaged by boat traffic or other happenstance, so preventing the tag from transmitting. If a fish died over deep water, the sinking fish would drag the tag to a depth

10.1071/MF01270 1323-1650/03/040435

where it would be crushed by the pressure. The above conditions made it impossible to assess to the fate of fish from which no transmission was obtained.

For this project, the PAT tag software was modified by the manufacturer (Wildlife Computers, Redmond, WA, USA) to release the tag and initiate transmission if it remains at a constant depth (e.g. surface or bottom) for a predetermined period of time. Additionally, two pressure release devices were developed that instantaneously release the tag if it sank below approximately 350 or 1500 m, depending on which device was used. Using these new tools, this study was designed to specifically address: (*i*) the fate of striped marlin caught and released on typical recreational tackle; (*ii*) the effectiveness of two different circle hooks and the traditionally used J-hooks; and (*iii*) the relative effect of circle and J-hooks on mortality.

Materials and methods

Description of pop-up archival transmitting tags

The PAT tag from Wildlife Computers was used in this study. These tags are devices that are secured to the fish and collect data on temperature (with a resolution of ±0.05°C), depth (from 0 to 1000 m at a resolution of ±0.5 m) and light intensity (measured as irradiance at 550 nm) every 2 min. Because of the limitation of Argos satellite transmission, the depth and temperature data are compressed into histograms before transmission. Light data is used to calculate geolocation for the fish during the deployment period. A status message is also transmitted to indicate whether the tag released early. At a predetermined time, the tag releases from the fish, floats to the surface and uploads summarized data to the Argos satellites.

Year 2000

This study was conducted offshore of Bahia Magdalena, Baja California Sur, Mexico, between 28 November and 3 December 2000. This region was selected because of the predictable concentration of striped marlin that occurs in these waters during the autumn months. In this first year of the project, 39 PAT tags were deployed.

Along with new pre-release software described above, a device was incorporated in the leader of the tag that immediately separated the tag from the fish if it sank into deep water. This device, termed an 'implosion link', consisted of a small glass tube (0.406 mm (16/1000 inch) wall thickness) sealed at both ends and partially filled with fluid (Preston Glass Industries, Glen Oaks, NY, USA). The implosion link was designed to break at a pressure equal to a depth of 350 m, which is a depth well below the known normal swimming range of striped marlin in the eastern Pacific (Holts and Bedford 1990) but less than the crush depth of the PAT tag (2000 m). The implosion links were tested in a hydrostatic pressure chamber where they consistently crushed at pressures equalling a depth of 350 m ± 7% (325–375 m). Stainless steel rings epoxied to the ends of the links allowed for incorporation into the tag leader, between the dart and the PAT tag (Fig. 1). Tags that were released as a result of the implosion link would then float to the surface and transmit after 3 days, triggered by the pre-release software.

Fishing for striped marlin took place on two private sportfishing yachts, the *Kelsey Lee* and the *Hana Pa'a*, both approximately 17 m in length. Fishing tackle was selected to be consistent with that most prevalent for this recreational fishery. Reels were spooled with Ande (West Palm Beach, FL, USA) 30-lb test monofilament line and drags were all set to 9 lbs with a spring scale. The J-hooks used were Eagle Claw 8/0 L317MGG (Denver, CO, USA) and the circle hooks were Eagle Claw 9/0 L2004F. These particular circle hooks were selected because the offset of the hook point relative to shank was minimal (5°). Degree of offset is thought to be an important factor affecting the incidence of deep hooking (Prince *et al.* 2002). Fish were caught by trolling a hookless teaser spread until marlin were raised, then a live mackerel was dropped back to the fish while the teasers were retrieved. The mackerel were either hooked through the nostrils or bridled on the top of the head with an elastic band. Only one fish was baited at a time to prevent multiple hook-ups. Once the bait was taken, the angler free-spooled the reel for several seconds, after which time J-hooks were aggressively set (putting reel in gear, winding line tight and pulling back with the rod), but circle hooks were set by simply winding the line tight as the fish swam away from the boat. This is the standard method for each hook type. All strikes and their outcome were documented. When fish were landed, the fight time, hook location, visually estimated size and general condition of the fish were recorded. Specific injuries or bleeding were noted. Fish were released by cutting the leader close to the hook and removing the hook whenever possible. No attempts to revive fish were conducted before release. Hook type was alternated between fish so that a nearly equal number of fish were caught with both hook types. The first 39 fish caught were tagged with PAT tags. Twenty PAT tags were deployed on fish caught with circle hooks and 19 caught with J-hooks. All fish were tagged with conventional tags.

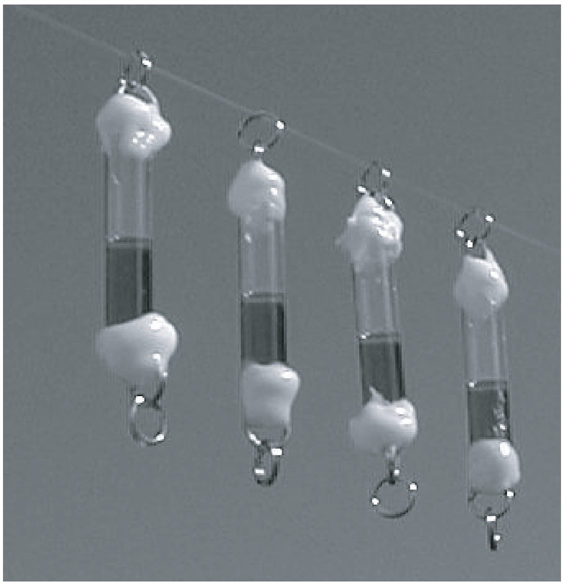

Fig. 1. Glass implosion links were placed between the dart and the pop-up archival transmitting tag, and were designed to break at or below 350 m to allow the release of the tag if the fish sank to deep water.

The PAT tags were programmed to detach and transmit after 1 month ($n = 8$), 3 months ($n = 8$), 6 months ($n = 8$), 9 months ($n = 7$) and 12 months ($n = 8$). Tags were rigged with the implosion link and a large plastic dart (Graves *et al.* 2002) attached with 50-lb monofilament line secured with knots. It is important to note that the rigged tags were positively buoyant and would float to the surface in the event that they were prematurely shed. Each fish was tagged with a PAT tag and a conventional tag, and both were placed just below and behind the first dorsal spine (Fig. 2), with the dart angled forward and through the dorsal midline. Tagging took place (with the aid of a tagging pole) once the marlin was controlled alongside the boat, with the fish remaining in the water. Fish were tagged with PAT tags regardless of condition.

Fig. 2. Striped marlin tagged with the pop-off archival satellite tag with implosion link (a) and a conventional tag (b). Note circle hook in the corner of the mouth (c).

Year 2001

Forty-one PAT tags were deployed in 2001 with several changes in tag rigging based on results from the previous year. We used a new pressure release mechanism designed and manufactured by Wildlife Computers. This guillotine-type device (RD1500) is designed to sever the leader at a depth of 1500 m. Nylon-coated, braided stainless steel cable was used for the leader in an attempt to eliminate the possibility of leader breaks. However, the RD1500 cannot cut through wire so a small loop of 300-lb monofilament was incorporated into the leader so that the guillotine would be effective (Fig. 3). By looping the monofilament through the attachment pin, the risk of the wire shorting the electrolysis that separates the tag from the leader was eliminated. Crimps were used to secure the leader. Two dart types were used, a medium-sized dart similar in design to that used in 2000 and a titanium dart manufactured by Wildlife Computers. Tags were programmed to pop-up after 1 month ($n = 20$), 2 months ($n = 10$), 3 months ($n = 10$) and 12 months ($n = 1$).

Fishing occurred off Bahia Magdalena in the autumn of 2001 between 6 and 10 December onboard the *Kelsey Lee* and the *Felina* (24-m sportfisher). Two types of Eagle Claw circle hooks were used; one had zero offset (L2004ELF) and the other was offset by 5° (L2004F, same hook used in 2000). The 0° offset hook is recommended by the Billfish Foundation for sailfish, the adults of which are similar in size to the striped marlin encountered at this study site.

Two additional changes in the methods were introduced in 2001. First, a number of fish were resuscitated before release to determine the potential impact of this on survival. Any striped marlin that were obviously exhausted or injured were held by the bill and pulled through the water by idling the boat forward. This effort was continued until the fish struggled against the restraint or showed no sign of improvement after 6 min. Second, because of the lower abundance of striped marlin in 2001, multiple fish were baited at a time to increase the total number of fish caught.

Analyses

The temperature and depth data obtained from the tags were used to determine the fate of the fish following release as well as to characterize the thermal profile of the water column. Analysis of the temperature/depth profile was most accurate using data from fish that died. The apparently slow rate of decent for these fish provided sufficient time for the temperature sensor to equilibrate at each depth. All data were analysed for normalcy and the mean and standard deviation reported unless otherwise indicated.

Fig. 3. Illustration of the tag rigging method.

Distance travelled was estimated based on the pop-up point and the amount of drift experienced by the tag. For those tags that released on time, or that sank and sat on the bottom for 3 days before release, the pop-up point was used to calculate the distance travelled. Tags that came off early spent 3 days floating at the surface before the pre-release function triggered. For these tags, distance travelled was estimated by calculating the direction and distance of drift for the tag for the 3 days after release, and subtracting the resulting vector from the point that the tag popped off. Error is difficult to determine and is dependent on changes in direction and velocity of the current.

We used χ^2 analyses to compare the three hook types with respect to effectiveness, where they lodged in the marlin (Yates' χ^2 was used in those cases where the expected frequency was less than 5 in more than 20% of cells) and mortality. For the purpose of this study, hook effectiveness is defined as the percentage of strikes that result in a landed fish. A landed fish is defined as a fish being brought to leader.

Results

In the first year of the study, 122 striped marlin were caught and released in 5 days of fishing. Pop-up archival transmitting tags were deployed on the first 39 fish caught. Estimated sizes ranged from 41 to 84 kg (mean 58 kg). On a few occasions, fish were conventionally tagged and the leader broken before hook location was noted, leaving 114 fish for which all details were recorded. Of these, 59 were caught on circle hooks and 55 were caught on J-hooks. In the second year, 5 days of fishing produced 50 marlin ranging from 41 to 77 kg (mean 51 kg). Of these, 26 were caught on 0° offset circle hooks (L2004ELF) and 24 were caught on 5° offset circle hooks (L2004F). The first 41 marlin caught were tagged with PAT

Table 1. Pop-up archival transmitting tag results for fish classified as survivors

Behaviour characteristics, including maximum swim depth, minimum swim temperature and distance travelled, for tagged fish from both years that were assessed to have lived are given. See text for pattern type definitions. Distance travelled was not available for fish numbers 888, 119 and 805. Fish no. 162 had poor message transmission, but the tag did not come off early and the fish was considered to be alive

Tag number	Study year	Pattern type	Number of days on	Intended duration (months)	Tag detached early	Distance travelled (nautical miles)	Maximum swim depth (m)	Minimum swim temperature (°C)
311	2001	3	93	3	No	381.7	104	14.4
142	2001	3	62	2	No	235.8	80	15.8
150	2001	3	62	2	No	256.0	132	14
164	2001	3	56	2	Yes	583.1	100	16
138	2001	3	54	2	Yes	198.7	180	13
149	2001	3	41	2	Yes	74.3	136	12.8
966	2001	3	37	3	Yes	358.5	132	15.6
106	2001	3	32	1	No	253.0	100	15
175	2001	3	32	1	No	381.0	>100, <150	>12.5, <15
72	2001	3	32	1	No	118.1	128	13.2
165	2001	3	32	2	Yes	111.0	116	15.8
70	2001	3	32	1	No	269.5	148	17
107	2001	3	31	1	No	394.5	108	15
76	2001	3	31	1	No	525.4	152	12.8
162	2001	3	31	1	No	NA	NA	NA
888	2001	3	31	3	Yes	NA	60	20.4
93	2001	3	27	1	Yes	624.9	84	15.4
793	2001	3	24	1	Yes	295.2	136	15.6
118	2001	3	17	12	Yes	214.9	136	15.6
168	2001	3	17	1	Yes	60.0	72	14.6
173	2001	3	14	1	Yes	316.3	160	13.8
121	2001	3	10	3	Yes	108.7	88	15.6
119	2001	3	10	1	Yes	NA	124	14.6
798	2000	3	10	12	Yes	84.4	96	13.6
851	2000	3	9	1	Yes	27.8	120	14.4
792	2000	3	8	3	Yes	113.9	96	15.6
809	2000	3	8	3	Yes	58.1	76	18.4
817	2000	3	8	6	Yes	63.7	80	14.8
846	2000	3	7	9	Yes	115.3	68	17.2
845	2000	3	7	9	Yes	43.3	100	16.2
843	2000	3	7	9	Yes	2.5	124	14.4
848	2000	3	6.0	3	Yes	41.5	72	16.8
960	2001	3	5.6	3	Yes	112.0	48	20
800	2000	2	5.4	12	Yes	110.1	192	11.6
790	2000	3	4.8	6	Yes	40.2	72	17.4
797	2000	3	4.1	1	Yes	45.1	76	18.2
805	2000	3	3.9	12	Yes	NA	60	20.2
94	2001	3	3.7	1	Yes	8.5	92	16.6
832	2000	3	3.7	6	Yes	64.2	84	19.0
844	2000	3	3.5	6	Yes	29.5	128	13.4
801	2000	3	3.1	6	Yes	11.4	112	15.6
852	2000	3	3.0	6	Yes	42.4	76	17.8
802	2000	3	2.4	12	Yes	8.0	96	15.6
1023	2001	3	2.2	1	Yes	47.6	112	14
837	2000	3	2.2	9	Yes	39.4	>60, <100	>15, <17.5

tags; 21 were rigged with plastic darts and 20 with titanium darts. In year 2, 26 fish were resuscitated; all but one of these was resuscitated for 3 min or less, and the remaining fish was revived for 6 min (mean revival time 1.8± 1.2 min).

Pop-up archival transmitting tag performance

In year 1, all 39 satellite tags were shed within 10 days. Although some early tag releases were a result of fish mortality (see below), the majority were simply shed ($n = 24$). Two of these first-year tags never transmitted. Despite changes to tag rigging in year 2, only 10 of the 41 tags remained on for the intended duration. Two tags successfully remained attached for a 2-month period and one tag remained attached for 3 months (Table 1). Excluding tags on fish that died (see below), the rest either did not transmit ($n = 10$) or were shed ($n = 16$) between 2 and 56 days (mean 24 ± 17)

Table 2. Pop-up archival transmitting tag results for fish classified as mortalities

See text for pattern type definitions. Maximum swim depth and minimum swim temperatures not available for tag numbers 804, 813, 853 because the fish died almost immediately. Insufficient data was available to determine distance travelled for tag numbers 796, 808, 813 and 855

Tag number	Study year	Pattern type	Depth sank to or released at (m)	Minimum temperature at release (°C)	Number of days	Intended duration (months)	Distance travelled (nautical miles)	Maximum swim depth (m)	Minimum swim temperature (°C)
813	2000	1	132	14.2	1.7	1	NA	NA	NA
811	2000	1	220	NA	1.4	3	8	NA	NA
887	2001	1	168	12.6	1.3	3	9	56	21.2
796	2000	1	128	13.4	1.0	6	NA	48	20.4
808	2000	1	188	11.8	0.9	1	NA	48	20.2
17	2001	1	660	6.4	0.8	3	9	36	21.2
74	2001	1	224	11.2	0.7	2	2	4	21.6
804	2000	1	204	12.2	0.0	12	1	NA	NA
853	2000	1	204	11.4	0.0	3	3	NA	NA
855	2000	1	108	14.2	0.0	9	3	NA	NA
854	2000	2	404	8.6	5.1	6	91	64	19.8
6	2001	2	1313	>5, <7.5	3.8	3	52	72	16.2
816	2000	2	>250, <350	>10, <12.5	3.0	1	70	76	17
847	2000	2	312	9.2	2.3	3	35	60	16.8
170	2001	2	1128	3.2	1.3	1	13	40	20.2
842	2000	2	416	8.4	1.1	9	18	56	20.2

Table 3. Pop-up archival transmitting tagged fish excluded from the study

See text for pattern type definitions. NA, Not available

Tag number	Study year	Status	Intended duration (months)	Number of days	Distance travelled (nautical miles)
815	2000	Pattern 3, tag was shed in less than 2 days	12	0.6	26.8
814	2000	Pattern 3, tag was shed in less than 2 days	9	0.8	36.7
803	2000	Pattern 3, tag was shed in less than 2 days	12	0.9	8.4
850	2000	Pattern 3, tag was shed in less than 2 days	3	1.2	18.4
807	2000	Pattern 3, tag was shed in less than 2 days	3	1.9	18.3
836	2000	Pattern 2, tag released at 244 m	12	2	11.3
849	2000	Low message transmission	1	8	NA
839	2000	Did not report	1	NA	NA
841	2000	Did not report	1	NA	NA
96	2001	Did not report	2	NA	NA
112	2001	Did not report	3	NA	NA
143	2001	Did not report	1	NA	NA
147	2001	Did not report	1	NA	NA
148	2001	Did not report	2	NA	NA
160	2001	Did not report	1	NA	NA
161	2001	Did not report	1	NA	NA
167	2001	Did not report	1	NA	NA
892	2001	Did not report	3	NA	NA
1043	2001	Did not report	3	NA	NA

after deployment (Tables 1–3). Another measure of tag performance is whether or not the tag transmitted usable data. For the purpose of this study usable data is defined as that which allowed us to determine the fate of the marlin; in many cases, this condition was satisfied, but more detailed behavioural data was not obtained (poorly transmitting tag). In the first year, 35 of the 39 PAT tags transmitted usable data; in year 2, only 31 of the 41 tags transmitted usable data.

Minimum temperature and maximum depth data

Minimum temperature and maximum depths experienced by individual marlin known to have survived provided a baseline that was then used for comparison against those fish suspected of perishing. The maximum depth encountered by healthy fish ranged from 48 to 192 m (mean 104.0 ± 30.3 m) (Table 1). The temperature/depth profiles obtained from fish that died over the area of capture, indicated that the mixed

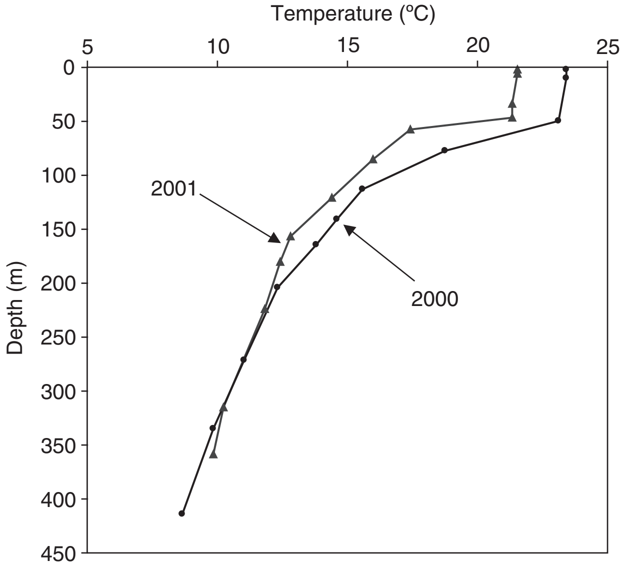

Fig. 4. Representative temperature–depth profile.

layer extended to approximately 50 m (Fig. 4) in both years. These water profiles may not represent more distant areas to which healthy fish moved.

Mortality analyses

Close examination of the maximum depth and minimum temperature records, in conjunction with time/date data, allowed us to determine the fate of 65 tagged marlin (Tables 1–2). Three characteristic patterns in the maximum depth and minimum temperature data were observed. Pattern 1: fish sank to a shallow bottom where the tag remained for 3 days, triggering the PAT tags early release software (Fig. 5*a*; $n = 10$); Pattern 2: fish sank to the activation depth of the implosion link/guillotine, causing the tag to be released and float to the surface, where it remained for 3 days before transmitting (Fig. 5*b*; $n = 8$); and Pattern 3: fish remained above the activation depth of the implosion link/guillotine and depth/time data indicates vertical movement until the tag separated from the fish or the tag released on the expected date (Fig. 5*c*; $n = 49$). Patterns 1 and 2 are indicative of death, whereas Pattern 3 is presumed to be that of a healthy fish. In all cases, there was a decline in temperature as depth increased, indicating that the depth sensor was functioning properly. It should be noted that two fish caught for this study were thought to be dead upon release. Both of these fish simply sank when released. Pop-up archival transmitting tags were attached to these fish to collect baseline data on known dead fish. The PAT tag on one of these fish never transmitted, however, we are including it in all the mortality calculations that follow.

Sixteen of the fish exhibiting Patterns 1 and 2 were classified as mortalities. Ten fish exhibited Pattern 1 (Table 2) and were classified as mortalities; they sank to the bottom in depths from 108 to 670 m. Eight fish exhibited Pattern 2 (Table 2), and six of these were classified as mortalities; the implosion link released tags from four fish at depths ranging from 300 to 416 m (mean 358.0 ± 60.4 m) and the guillotine released tags from two fish at 1128 m and 1313 m. The two remaining Pattern 2 fish had their implosion link-rigged tags release at depths shallower than we would have expected. It is possible that the implosion link malfunctioned on these two fish. One released at 244 m (tag no. 836; Table 3) and another at 192 m (tag no. 800; Table 1). Fish no. 800 was in excellent condition when released and carried the tag for 5.4 days before shedding, and the time/depth/temperature data

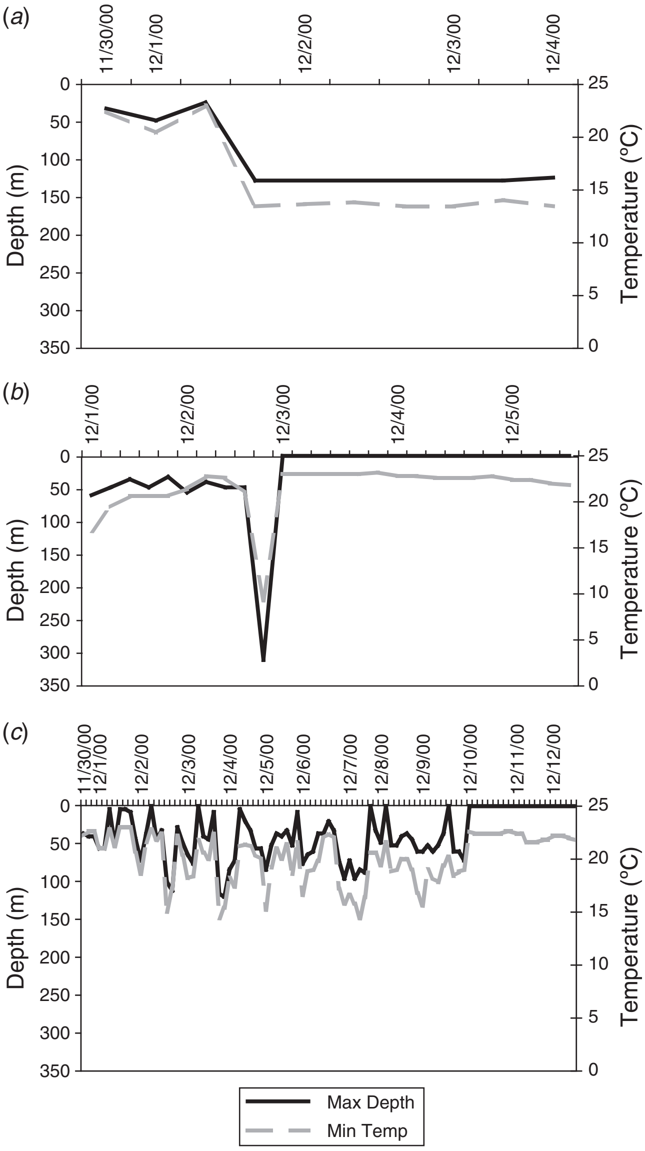

Fig. 5. Maximum depth and minimum temperature profiles for fish that: (*a*) died and sank to the bottom where it remained for 3 days before its release; (*b*) died and sank to a depth where the glass link imploded and the tag released, floated to the surface and remained for 3 days before reporting; and (*c*) remained above the implosion depth of the link and was interpreted at being healthy.

compared with that of known healthy fish (Pattern 3). Fish no. 800 only went 12 m deeper than the next deepest known surviving fish, so we have classified it as a survivor. Except for slight bleeding from the hook wound, fish no. 836 was also in excellent condition upon release. Since the tag was shed after only 1 day and the depth at which the tag released for this fish was 64 m deeper than the deepest dive depth for the rest of the samples (Table 3), we have eliminated this fish from the sample because of uncertainty. The time between release and death for all mortalities ranged from immediately to 5 days (mean 1.5 ± 1.2 days), with 75% of mortalities occurring in less than 2 days and 94% occurring in less than 4 days. Fish that were bleeding from the gill chamber lived an average of 0.7 days (±1.1), fish that were gut hooked lived an average of 1.0 days (±0.7) and fish that were released apparently healthy lived and average of 2.9 days (±2.0).

Forty-nine fish exhibited repeated shallow dives that are indicative of a healthy swimming fish (depths no greater than 180 m and temperatures no less than 12.8°C; Table 1) throughout the time they carried the tag (Pattern 3). Thirty-nine of these fish shed the tag before the programmed release date (Table 1). Five of the tags were eliminated from the study because they were shed after less than 2 days; a time span within which 75% of documented mortalities occurred. The remaining 44 fish were classified as healthy survivors.

Given the above results, the total number of surviving fish was 45 and the total number of mortalities was 15. Adding the single specimen released dead for which we have no tag data, brings the total mortality for the study to 16 of 61, or 26.2% (Table 4). The different years of the study had different mortality rates. In the first year it was 36.6% (11 of 30) and in the second year it was 16.1% (5 of 31) (Table 4).

Table 4. Documented mortality rates

Adjusted mortality excludes mortalities not related to the hook type (handling or fight time); total mortality was not adjusted because it measures the total fishery-related mortality

Hook type	Year	Mortality rate (%)	Adjusted mortality (%)
5° Offset circle hook	2000	33.3	29.4
5° Offset circle hook	2001	7.7	7.7
5° Offset circle hook	All	22.6	20.0
10° Offset J-hook	2000	33.3	29.4
0° Offset circle hook	2001	17.7	12.5
Combined circle hook	2001	16.1	10.3
Combined circle hook	All	20.8	17.4
Total mortality	2000	36.6	–
Total mortality	2001	16.1	–
Total mortality	All	24.2	–

Ten of the 16 documented mortalities (63%) were noted as seriously injured upon release; seven were bleeding from the gill cavity and five were gut hooked (three of these were also counted as bleeding from the gill cavity). Another of the mortalities was bleeding from a minor flesh wound (tear in the dorsal fin) caused by the monofilament. The remaining six were noted to be in good condition upon release. For comparison, 100% of the fish that exhibited bleeding from the gill cavity perished and 63% of deep hooked fish perished ($n = 8$), while bleeding from flesh wounds (damage from hook or monofilament) occurred 10 times and only one of these fish died. One of these 10 had a punctured eye and survived 10 days before shedding the tag. A single fish with an extraordinarily long fight time (150 min, 6 times longer than average, see below) was one of the six non-injury-related mortalities. Nine percent of the fish that were apparently healthy when released died.

Hook comparison

Over the 2 years of the study, 276 marlin strikes were recorded (L2004F = 139, L2004ELF = 44, L317MGG = 93) (Table 5). There was no difference in effectiveness between the three hook types (χ^2-test $P = 0.97$); about 80% of striking fish were hooked for each of the hook types and 61–63% of the strikes resulted in a fish being landed. There was, however, a difference in where the hook lodged in the marlin. Both circle hook types lodged in the mouth 70% of the time or greater compared with 50% for J-hooks. Gut hooking (considered to be anywhere below the throat that could not be directly observed) was more than 2.5 times as prevalent for J-hooks than for circle hooks. Over 5 times as many fish caught on J-hooks were observed to be bleeding from the gill cavity compared with the circle hooks. The relatively small sample size for the L2004ELF hook (non-offset circle) did not allow for robust statistical comparison. However, when comparing the offset circle hook to the J-hook, it was determined that the J-hook had a statistically lower occurrence of mouth hooking ($P < 0.01$), and a higher probability of both gut hooking ($P < 0.01$) and gill hooking (Yates' $P < 0.02$), as well as a higher probability of causing bleeding from the gill cavity ($P < 0.01$). There was not, however, a statistical

Table 5. Overall comparison of fish catch information of circle and J-hooks

L2004F, 5° offset circle hook; L2004ELF, 0° offset circle hook; L317MGG, 10° offset J-hook; landed, brought to leader; deep hooked, anywhere below throat; mouth hooked, bill, upper jaw, lower jaw, corner and roof

Hook type	No. of strikes	Landed (%)	Mouth hooked (%)	Gut hooked (%)	Gill hooked (%)	Foul hooked (%)	Bleeding (%)
L2004F	139	63	80	5	0	2	3
L2004ELF	44	61	70	7	0	0	4
L317MGG	93	62	50	19	9	3	21

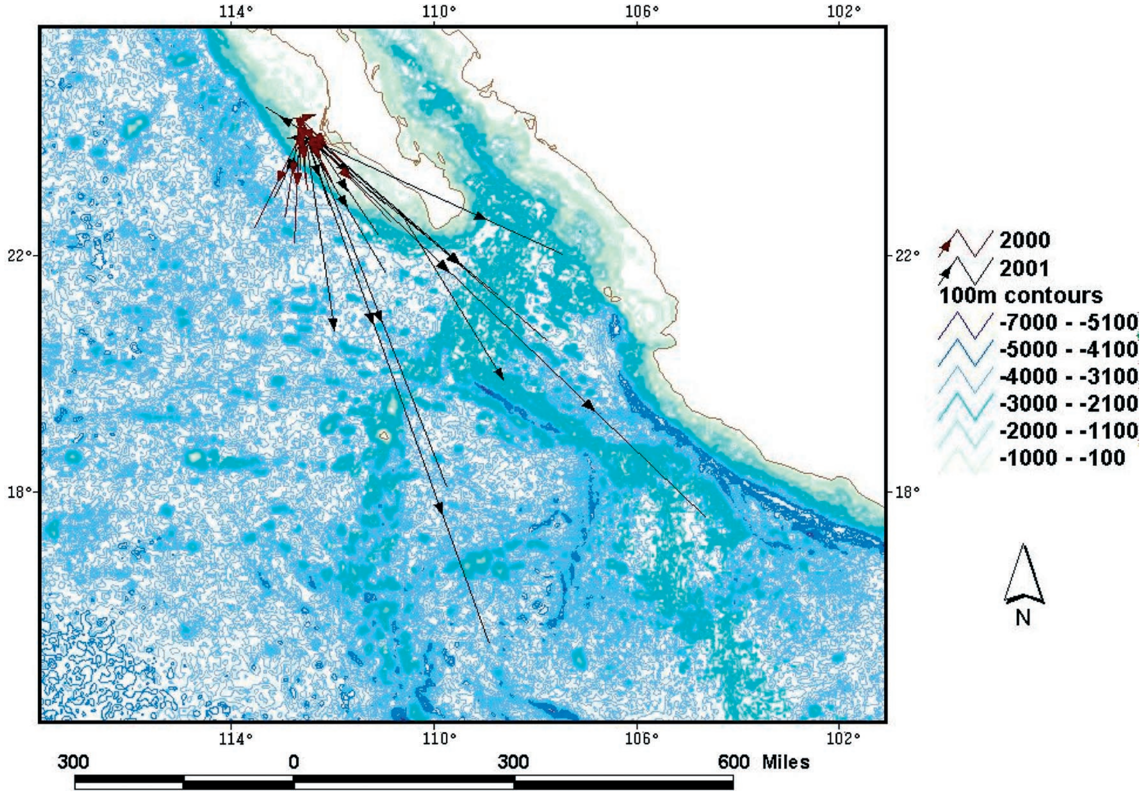

Fig. 6. Map showing all striped marlin tagged in 2000 and 2001 that were categorized as live, showing the movement between the tagging point and the pop-up point.

difference in the number of fish that became throat hooked (Yates' $P = 0.34$), or that became foul hooked (Yates' $P = 0.43$). There was also no difference in mortality rates between the circle hook and the J-hook (Yates' $P = 0.55$; Table 2). The same statistical results occurred when the two circle hook types were combined into a single sample for comparison to the J-hook. Although the non-offset circle hook was found to be equally effective in catching striped marlin, it should be noted that the smaller gauge wire of this hook did result in some bent hooks.

Fight time

The fight time for all fish released with PAT tags ranged from 5 to 150 min, with a mean of 26 min (±21). The fight time for fish that died (mean 27.2 ± 33.5) was not statistically longer than for those that survived (mean 23.5 ± 12.9) (one-tailed Mann–Whitney U-test, $U = 433$ and $P = 0.31$). There were two extraordinary fight times of 126 and 150 min; the next longest fight time was 56 min. The fish with the fight time of 150 min perished and the fish with the fight time of 126 min was never heard from.

Reviving fish

During 2001, a total of 23 fish were deemed candidates for revival. These fish were revived for periods of 1–6 min. Tags from six of these fish never transmitted. Of the remaining 17 fish, three were documented mortalities (18%), compared with two mortalities out of 14 fish that were not revived (14%).

Dart performance

The two dart types (the large and medium-sized nylon darts were combined into a single sample) were analysed for differences in tag shedding. There was no significant difference in tag shedding between the titanium dart and the nylon dart (χ^2-test; $P = 0.11$).

Fish movement

Healthy fish moved an average of 10 nautical miles (±6) per day (Table 1). Fish generally moved away from Bahia Magdelana in a southerly direction (Fig. 6).

Discussion

We made three basic assumptions to determine the fate of all striped marlin for which data was obtained. Assumption 1: individuals that sank to the bottom very soon after release, and remained there for 3 days, were dead. Assumption 2: individuals for which the implosion link or RD1500 released the tag at depth were dead. Assumption 3: individuals that did not travel below 200 m, but had the tag come off prematurely were considered to have survived. Assumption 1 requires no further discussion, given that the tags are positively buoyant and could have sunk only if attached to a dead fish.

Assumption 2 is stated as a function of depth because it is a value for which we have data and is the key in triggering the release mechanism. This assumption actually encompasses a combination of factors that vary with decreasing depth, including temperature, light, oxygen and pressure. Cold temperature and low oxygen level are the most critical factors that would restrict a normally shallow water species from making excursions into relatively deep water (Sund 1981; Brill 1994). Unfortunately, no information is available on the oxygen requirements of striped marlin or the oxygen profile of our study site. The data on depth/temperature distributions for striped marlin are also limited. There are, however, data from other regions that provide insight into the habitat preferences of striped marlin. Minimum temperatures and maximum depths experienced by acoustically tagged striped marlin off southern California were near 10°C at about 90 m (Holts and Bedford 1990). In a study off Hawaii, Boggs (1992) used a longline equipped with hook timers and temperature depth recorders to determine the catch-depths for striped marlin. All fish were caught above 240 m, with only two fish obtained below approximately 140 m. Also off Hawaii, Brill *et al.* (1993) found that six striped marlin spent 85% of their time above 90 m, with the deepest dive to approximately 170 m. The striped marlin we considered healthy never exceeded a maximum depth of 192 m. As for temperature, the lowest value was 11.6°C. Combining the temperature and depth data, it is highly improbable that any healthy fish descended to the 350 m implosion depth of the glass link or to 10°C at this depth. Three hundred fifty meters is over 100 m deeper than any depth ever reported for a striped marlin. We amassed a total of 918 days of data from our PAT tagging, with summary resolution as fine as hourly. The size of our data set provides some confidence with respect to conclusions based on Assumption 2. The role temperature, light and oxygen play in restricting the movements of striped marlin is a topic for further investigation.

Assumption 3 includes 16 fish that shed their tags after a period of time equal to or less than the longest documented time between release and death (5 days) for those fish that were determined to have died. We eliminated five of these fish from our study because they lost their tags in less than 2 days; the time period where 75% of mortalities occur. The remaining 11 fish that shed tags in less than 5 days were classified as survivors. This decision was based on probability as well as the strong relationship we found between injury and death. These 11 fish were in good condition when released and they exhibited no excursions into unusually cold or deep water. We believe that removing these 11 fish from our sample would have artificially inflated the rate of mortality; consequently, by including them in our list of survivors, our estimate of mortality is conservative.

Deaths that occurred soon after release are easily attributed to the direct results of injuries obtained when caught. In fact, all of the fish that died immediately were bleeding upon release. It is difficult to speculate the exact cause of death in fish that lived longer (up to 5 days). There are a number of possibilities, including physiological stresses associated with oxygen debt, internal bleeding, infection and predation. Predation could cause mortality in a weakened fish that would have otherwise recovered.

The effect of the PAT tag on the likelihood of an individual falling victim to predation also deserves mention. It is reasonable to surmise that a fish dragging the relatively large PAT tag might attract more attention from a predator than otherwise. Predation on tagged fish could result in a destroyed tag, a tag that floats to the surface or a sinking tag. The fact that predation could result in a tag floating to the surface does allow some possibility that individuals we have determined to survive did in fact perish. Predation may explain the fate of some of the PAT tags that failed to transmit. In a number of acoustic tracks of billfish, tagged fish have been killed by sharks (Block *et al.* 1992*a*; Pepperell and Davis 1999). Catch and release-associated mortality may be higher in regions with relatively high densities of large sharks. For example, anglers at the Great Barrier Reef, Australia, routinely lose black marlin to sharks as the fish is being fought to the boat; fish released in a weakened condition may be easier prey for these same sharks.

Hook-related injuries had a direct impact on survival. The pop-up satellite tag data described in this study was useful in providing a relationship between the condition of individual fish upon release and the probability of that fish surviving. These data can now be used as a means to independently calculate the mortality rate of the entire sample of 172 released marlin. To do this, we apply a 100% mortality rate to fish released bleeding from the gill chamber (14 × 1.0), a 63% rate to fish that were deep hooked (18 × 0.63), and a 9% mortality rate to fish released apparently healthy (140 × 0.09). This exercise predicts that 38 out of 172 (22%) released marlin died. This estimated value compares favourably with the value derived from the PAT tag deployments (26%).

The mortality rate we documented is higher than that reported for studies using acoustic telemetry. Although mortality estimates range from 0% to 50% (summarized in Pepperell and Davis 1999), most studies found rates of mortality to be between 0% and 17%. There are a number of reasons why previous acoustic telemetry studies may result in an underestimate of mortality. First, tracks are on the order of hours to a few days; we found fish to die up to 5 days after release. Second, because these studies were not specifically designed to document mortality, efforts were made to tag only fish that appeared healthy, resulting in a biased estimate. Third, tags that sink to the bottom and remain stationary are often considered to have fallen off the fish. However, it is difficult to determine conclusively that the fish did not perish. Fourth, the sample size for most acoustic telemetry studies is less than 10. Consequently, by increasing our overall sample size to 80 tags, this study provides a more accurate estimate of mortality for striped marlin.

Our hook comparisons agree with other studies that have been performed to date (Grover *et al.* 2002; Lukacovic and Uphoff 2002; Prince *et al.* 2002) in that circle hooks are effective and have a significantly higher probability of lodging in the mouth. We found circle hooks to be equally effective in catching striped marlin as J-hooks. Moreover, fish landed on circle hooks had fewer of the injuries we have associated with post release mortality. We did not find, however, a significant difference between the mortality rates of fish caught on circle hooks versus J-hooks. Also, we did not find any difference between offset and non-offset circle hooks. These findings could be a result of sampling error within a relatively small sample size, or it could indicate circle hooks are doing internal damage before eventually lodging in the mouth. The bend in the shank of circle hooks may allow these hooks to pull out of soft tissue easier than J-hooks; if true, this could result in circle hooks initially lodging in the gut and then pulling free and hooking again in the mouth. This possibility should be explored with a species that can be kept in captivity for observation and necropsy. Another factor that needs future attention is the effects of the different fishing methods used for J-hooks and circle hooks. Fishermen do not aggressively set the hook when using circle hooks because of the belief that this pulls the hook from the fish's mouth. What would be the result of fishing J-hooks in the same manner?

There was a difference in mortality rates between the different years of the study (2000: 36.6%; 2001: 16.1%). Although the mortality rate was lower in 2001, the incidence of tags that did not report was much higher. These non-reporting tags could have been damaged as a result of predation on fish that died; since these tags were thrown out of the study, the mortality rate in 2001 could be higher than reported. If real, the lower mortality rate may be explained by the addition of resuscitation in year 2, although this effect is difficult to measure. Initially, we had hoped to revive all fish during the second year so that we would have two clear treatment groups. However, it was realized that this was not possible; fish that did not require resuscitation were at risk of injury through needless handling. We were forced to abandon these efforts on strong/healthy fish. As a result, it is not possible to clearly analyse the effect of resuscitation since the treatment group was compromised because of injury or fatigue, whereas the non-treatment group was apparently healthy. More study is required to determine if there is a clear benefit in reviving fish. There was a higher incidence of severe injury to fish that perished in year 1 (73%) compared year 2 (40%), suggesting that that random events may have caused the disproportionate mortality rates between our study years. In fact, two fish died in year 1 as a result of handling alongside the boat rather than injury incurred from the hook (an additional form of fishery mortality).

Fight time did not prove to be significant with respect to mortality. The tackle we selected was well matched to the size of the fish being caught, so extraordinarily long fight times were very rare. On the two occasions fish were fought for over 2 h, one resulted in mortality and the other was never heard from. Not much can be made of the single documented mortality, but a future study of light tackle fishing may prove fight time to be significant with respect to fish health.

The high rate of PAT tag failure that we experienced deserves some mention. Although changes we made in year 2 improved tag retention somewhat, tag retention still remains a major problem for studying movement patterns in this species. Despite steel cable, an improved pressure release mechanism and three types of dart, very few tags remained on the fish for the expected duration. The most likely explanation is that the attachment point of the PAT (a hollow stainless steel pin) is breaking under stress of breaching (a commonly observed behaviour at our study site) or as a result of other fish striking the tag. Since our study was completed, Wildlife Computers has modified the attachment point of their PAT tags to make them more robust—hopefully, helping to solve the problem.

The recreational fishery for striped marlin in the eastern Pacific is unique in that it is primarily a live bait fishery. Recreational anglers prefer to capture marlin with bait as opposed to trolling, but this is not a feasible method in most other marlin fisheries. Our data indicate that at least one in four striped marlin caught and released with live bait do not survive. This value is much greater than was indicated by a similar study conducted for blue marlin (Graves *et al.* 2002). A likely cause of this difference is the fact that Graves *et al.* (2002) tagged fish that were caught by trolling artificial lures. Troll-caught fish are rarely hooked anywhere but the mouth, greatly reducing the chances of severe injury. Differences in the study species (blue marlin are much larger than striped marlin) or differences in sample size could also contribute to the difference between the studies. Interestingly, a study in progress has resulted in the mortality of three out of nine black marlin tagged with PAT tags during the autumn of 2002 off the Great Barrier Reef (M. L. Domeier, personal observation; J. S. Gunn and J. G. Pepperell, personal communication).

Our observations allow for the suggestion of some guidelines that would reduce mortality of striped marlin. When fishing with live or dead bait, anglers should be encouraged to use circle hooks. They are equally effective and far less likely to cause serious injury. Striped marlin that are bleeding from the gill chamber should be retained and consumed because in our study fish in this condition did not survive. Caution should also be taken when handling marlin at the leader; fish brought in too soon will be more prone to mortal injury as a result of striking the side of the boat.

The results from this study also allowed us to develop a protocol for tagging striped marlin to minimize the chances of tagging a fish that will subsequently die. The protocol is as follows: (*i*) do not tag fish that are bleeding from the gill cavity (minor flesh wounds can be assessed on a case by case basis); (*ii*) do not tag fish hooked in the gut; (*iii*) do not tag fish that that took more than 30 min to land; and (*iv*) do not tag fish in cases where the stomach protrudes from the mouth. When following this protocol for a study of migratory patterns in striped marlin (autumn of 2002 and work in progress), the senior author observed zero mortality for 30 tags deployed.

Acknowledgments

This work would not have been possible without the generous support of the Offield Family Foundation and the George T. Pfleger Foundation. Thanks to Captain John Talsky and crew on the *Kelsey Lee*, Captain John Howell and crew on the *Hana Pa'a*, and Captain Tony Nungary and crew on the *Felina*.

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Manuscript received 12 September 2001; revised and accepted 14 January 2003.