Journal of Experimental Marine Biology and Ecology xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Journal of Experimental Marine Biology and Ecology

journal homepage: www.elsevier.com/locate/jembe

Satellite transmitter attachment techniques for small juvenile sea turtles

Erin E. Seney [a,b,*], Benjamin M. Higgins [c], André M. Landry, Jr. [a,b]

[a] Sea Turtle and Fisheries Ecology Research Laboratory, Texas A&M University at Galveston, 5007 Avenue U, Galveston, TX 77551, United States
[b] Department of Wildlife & Fisheries Sciences, Texas A&M University, 2258 TAMU, College Station, TX 77843, United States
[c] NOAA Fisheries Sea Turtle Facility, Southeast Fisheries Science Center, 4700 Avenue U, Galveston, TX 77551, United States

ARTICLE INFO

Article history:
Received 7 September 2009
Received in revised form 31 December 2009
Accepted 5 January 2010
Available online xxxx

Keywords:
Attachment
Epoxy
Growth
Neoprene
Satellite tracking
Sea turtle

ABSTRACT

Three trials comprised of 4, 16, and 8 captive-reared juvenile loggerhead sea turtles (*Caretta caretta*) were run for 164, 134, and 213 d, respectively, to evaluate platform terminal transmitter (PTT) attachment methods. Power-Fast® epoxy-only (PF-only) and Power-Fast®/Sonic-Weld® epoxy putty (PF/SW) protocols were tested in each trial, and the latter trials also included experimental, less-rigid methods incorporating 1.5 and 3.0 mm neoprene. Protocols were modified slightly for the latter trials compared to those of the first, utilizing coarser sandpaper for site preparation and discarding initial "squeezes" of epoxy.

Despite a low average growth rate (0.012 cm/d), three of four PTTs were shed from the loggerheads in Trial 1. All PTTs remained attached in Trial 2 after an average straight carapace length (SCL) increase of 3.4 cm (0.024 cm/d), suggesting that protocol modifications improved upon Trial 1 methods. One 3.0-mm neoprene attachment and a PF-only attachment were shed during Trial 3 after SCL increases of 3.7 and 5.4 cm, respectively. The other six PTTs remained attached after an average SCL increase of 9.6 cm (0.045 cm/d), but significant gaps occurred along the perimeters of the three remaining non-neoprene attachments. Two neoprene attachments became loose along the edges while their centers remained secure, suggesting that carefully-applied neoprene attachments may be beneficial for tracking smaller, faster-growing sea turtles.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Sea turtles' life history strategies and migratory habits not only make them vulnerable to anthropogenic threats but difficult to monitor and study (Chaloupka and Musick, 1997; Witherington, 2003). Satellite telemetry is a powerful tool for examining long-term movements of these protected species and enhancing conservation and management efforts (Coyne and Godley, 2005; Godley et al., 2008). A variety of methods have been developed to deploy satellite transmitters on sea turtles over the past three decades. Attachment protocols for hard-shelled sea turtles have included, but are not limited to, tethering buoyant transmitter housings to the posterior end of the shell (Stoneburner, 1982; Timko and Kolz, 1982) and attachment of "backpack" style transmitters to the anterior vertebral scutes with fiberglass cloth and polyester resin (Byles and Keinath, 1990; Renaud et al., 1993; Balazs et al., 1996; Kobayashi et al., 2008), fiberglass filler (Mansfield et al., 2009), two-part epoxies and putties (Byles and Keinath, 1990; Beavers et al., 1992; Godley et al., 2003; Seney and Landry, 2008; Mansfield et al., 2009), and combinations of these adhesives. Newer methods have attempted not only to maximize transmitter retention, but also to minimize detrimental effects on the turtle by limiting exposure to high curing temperatures (Byles and Keinath, 1990; Renaud et al., 1993) and reducing drag with more hydrodynamic transmitter/adhesive profiles (Godley et al., 2003; Seney, 2008; Mansfield et al., 2009).

Most sea turtle tracking research published to-date has focused on post-nesting females because this life history stage is easiest to locate and tag (Godley et al., 2008), but there is growing interest in satellite tracking smaller immature individuals (e.g., Godley et al., 2003; Kobayashi et al., 2008; Mansfield et al., 2009). Recent tracking efforts targeting immature individuals have been facilitated by advances in transmitter miniaturization (Hays et al., 2007) and motivated by the significance of this life history stage to the recovery of many sea turtle populations (Turtle Expert Working Group, 2000; Heppell et al., 2007). Knowledge of immature individuals' temporal and spatial movement patterns is of utmost importance to the development, evaluation, and adaptation of management strategies because these individuals represent a central life history stage that may be vulnerable to at-sea risks such as fisheries bycatch (Witherington, 2003; Heppell et al., 2007).

Backpack-style platform terminal transmitters (PTTs) were deployed on eight Kemp's ridley sea turtles (*Lepidochelys kempii*) during 2004–2005 to examine their movements. Three adult females and five immature conspecifics were satellite-tracked in the western Gulf of Mexico for considerably shorter periods than anticipated ($\bar{x} \pm 1$ SD $= 38 \pm 15$ d, $n = 8$) after transmitters were attached with Power-Fast®+ two-part marine epoxy (Seney, 2008). Several different transmitter models were utilized, but battery lives of at

* Corresponding author. Sea Turtle and Fisheries Ecology Research Laboratory, Texas A&M University at Galveston, 5007 Avenue U, Galveston, TX 77551, United States.
E-mail address: eeseney@gmail.com (E.E. Seney).

0022-0981/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jembe.2010.01.002

ARTICLE IN PRESS

least 6–12 months were expected. Although it is possible to infer the cause of tag failure using diagnostic data collected by some larger transmitters (Hays et al., 2007), the smaller units deployed in this study did not collect such data; however, examination of Argos data (Location Class, Index of Quality, and Number of Messages for individual locations) indicated that one of the eight transmitters was floating at the surface prior to cessation of transmissions and therefore a probable turtle mortality (Hays et al., 2003; Seney, 2008). Battery data (voltage and transmission current drain) were acquired from the latter three PTTs deployed (Sirtrack KiwiSat 202 units on immature ridleys), and none indicated battery failure as a cause of transmission cessation. The discrepancy between anticipated and actual average track durations prompted concerns regarding causes for premature transmission loss including antenna damage (Seney, 2008), biofouling (Troëng et al., 2006), and attachment failure, as well as turtle mortality (Hays et al., 2003, 2004; Chaloupka et al., 2004; Seney and Landry, 2008). Integration of antifouling paints (Seney, 2008) and a second adhesive, Sonic-Weld® steel-reinforced epoxy putty (Mansfield, 2006), in 2006 increased track duration for adults ($p=0.05$) but not for juveniles ($p=0.87$). Shorter than anticipated track durations have also been observed for juvenile Kemp's ridleys and green turtles (*Chelonia mydas*) along the middle and lower Texas coast (Metz and Landry, unpubl.) and juvenile green turtles in Florida (A. Stamper, pers. comm. to EES).

A potential cause for track duration differences among different-sized turtles is the decreased growth rate observed with age. Sea turtle growth has been fit to several parametric age-based models, including the von Bertalanffy, Logistic, and Gompertz growth functions (Chaloupka and Musick, 1997). These functions depict asymptotic growth, with rapid growth rates at younger ages/sizes followed by decreasing growth rates as the curve approaches an asymptote. Both Kemp's ridley and loggerhead sea turtles (*Caretta caretta*) have exhibited rapid growth rates in captivity during the first two years of life at the NOAA Fisheries Sea Turtle Facility (NOAA STF; Higgins, 2003), and asymptotic growth has been observed for recaptured captive-reared (Caillouet et al., 1995) and wild Kemp's ridleys (Zug et al., 1997; Snover et al., 2007). Long-term mark-recapture studies in Florida have yielded ridley SCL growth rates of 5.9–8.8 cm/y offshore Cape Canaveral, 3.6–5.4 cm/y in the Cedar Keys, and 1.8–12.2 cm/y in Gullivan Bay (Schmid and Witzell, 1997; Witzell and Schmid, 2004). In the latter study, ridleys measuring 20.0–39.9 cm SCL grew significantly faster than did those 40.0–59.9 cm SCL (Witzell and Schmid, 2004). Growth rates of Atlantic loggerheads have also been shown to decrease with increasing carapace length (Bjorndal et al., 2003).

Rapid growth of immature sea turtles may increase the carapace surface area underneath a PTT in a short time. The resulting stress on rigid adhesives may cause the transmitter to become unattached in a shorter time period than would a similarly attached transmitter on a mature, slower-growing conspecific. As such, less-rigid methods may prove effective for maintaining PTT attachment integrity and, in so doing, increase transmission duration for immature turtles. Likewise, attachment site preparation may be more important for smaller, faster-growing individuals than that for larger conspecifics. Herein, we report results of trials examining transmitter attachment integrity and less-rigid, experimental attachment protocols.

2. Materials and methods

The NOAA STF in Galveston, Texas concurrently houses multiple year classes of loggerhead sea turtles (Higgins, 2003), providing the opportunity to examine multiple PTT attachment techniques on healthy, same-age sea turtles, as opposed to opportunistic use of wild Kemp's ridleys undergoing rehabilitation. Three attachment trials were conducted with captive-reared juvenile loggerhead sea turtles at the NOAA STF. In the first, four 29-month old loggerheads averaging 40.1 cm SCL (SD=1.3 cm) were outfitted with replica (dummy) PTTs on 10 January 2006 to compare two attachment methods. Dummy Sirtrack KiwiSat 202 PTTs (approximately 8×4×2 cm) were attached along the first two vertebral scutes with Power-Fast®+ two-part marine epoxy (PF-only, $n=2$) or Power-Fast® covered with Sonic-Weld® steel-reinforced epoxy (PF/SW, $n=2$; Mansfield, 2006; Seney and Landry, 2008). These loggerheads were held at the NOAA STF in a divided raceway from 10 January to 23 May 2006 (134 d) and maintained according to NOAA STF husbandry standards (Higgins, 2003). Transmitter attachments were examined for integrity and photographed weekly, and turtles were measured monthly.

The second attachment trial examined the PF-only and PF/SW methods as well as experimental techniques incorporating neoprene (Fig. 1). Twenty 30-month old captive-reared loggerheads, averaging 43.6 cm SCL (SD=1.0 cm), were randomly assigned to a control group (no PTT) or one of four attachment types: PF-only, PF/SW, and two experimental methods integrating 1.5 mm neoprene and 3.0 mm neoprene. The control group consisted of 4 loggerheads, and the other 16 were subsequently outfitted with dummy KiwiSat 202 PTTs on 2–3 February 2007. Protocols used to attach the four PF-only and four PF/SW units matched those used in 2006 with two exceptions: (1) 60-grit sandpaper was utilized instead of 100-grit to sand the attachment site and sides and underside of the PTT and (2) the first 10–15 cm of Power-Fast®+ discharged from the applicator nozzle was discarded because it may not cure properly (R. Morehead, unpubl.). The remaining eight turtles were split evenly between the two neoprene treatments. Pieces of 1.5 mm (1.5 mm group) and 3.0 mm (3.0 mm group) neoprene with nylon backing were cut 3–4 cm larger than the base of each dummy PTT, resulting in pieces approximately 14×10 cm with rounded edges. An outline of the neoprene was traced onto each turtle's carapace at the attachment site, overlapping the first and second vertebral scutes. "Mega blue" (also called "sensor-safe") room-temperature vulcanizing (RTV) silicone was then used to outline the scutes at the attachment site, acting as a barrier to epoxy along these areas of shell growth (Fig. 1a). Once the silicone set, Power-Fast®+ was applied at the attachment site, avoiding the silicone and thereby allowing for less-encumbered growth along the scutes' suture lines (Fig. 1b). The neoprene was then carefully placed on top of the epoxy, nylon side up (Fig. 1c), and, once this attachment was secure, the transmitter was attached to the neoprene with Power-Fast®+ (Fig. 1d). The 20 loggerheads were evenly distributed among four raceways (1 of each attachment and 1 control per raceway) and maintained under NOAA STF husbandry protocols (Higgins, 2003) through 17 May 2007 (Day 105). PTTs were manually checked and photographed weekly, whereas turtles were measured monthly.

A third trial was conducted to further examine effects of carapace growth on the four attachment types. Eight 23-month old captive-reared loggerheads, averaging 36.8 cm SCL (SD=0.9 cm), were outfitted with dummy KiwiSat202s (two per attachment type, randomly assigned) on 20 July 2007. The turtles were housed in two raceways, maintained under NOAA STF husbandry protocols (Higgins, 2003), and fed to achieve high growth rates. Attachments were checked manually each week and photographed every 1–2 weeks. All turtles were measured monthly and when their PTTs were shed. Once an individual lost its PTT, food rations were reduced to that of the general population, and the turtle was no longer included in growth measurements.

Loggerheads in the first two trials were transported overnight 23–24 May 2006 (Days 134–135), and 17–18 May 2007 (Days 105–106), respectively, from Galveston to Panama City, Florida for use in NOAA's annual turtle excluder device testing. Upon arrival, they were placed in outdoor pens for "semi-wild" conditioning (Higgins, 2003) and monitored for transmitter loss. PTTs that remained attached were removed prior to July 2006 and July 2007 releases in Sebastian Inlet, Florida. In the third trial, PTTs that remained attached on 17 February 2008 (Day 213) were removed to facilitate use of the turtles in

Please cite this article as: Seney, E.E., et al., Satellite transmitter attachment techniques for small juvenile sea turtles, J. Exp. Mar. Biol. Ecol. (2010), doi:10.1016/j.jembe.2010.01.002

ARTICLE IN PRESS

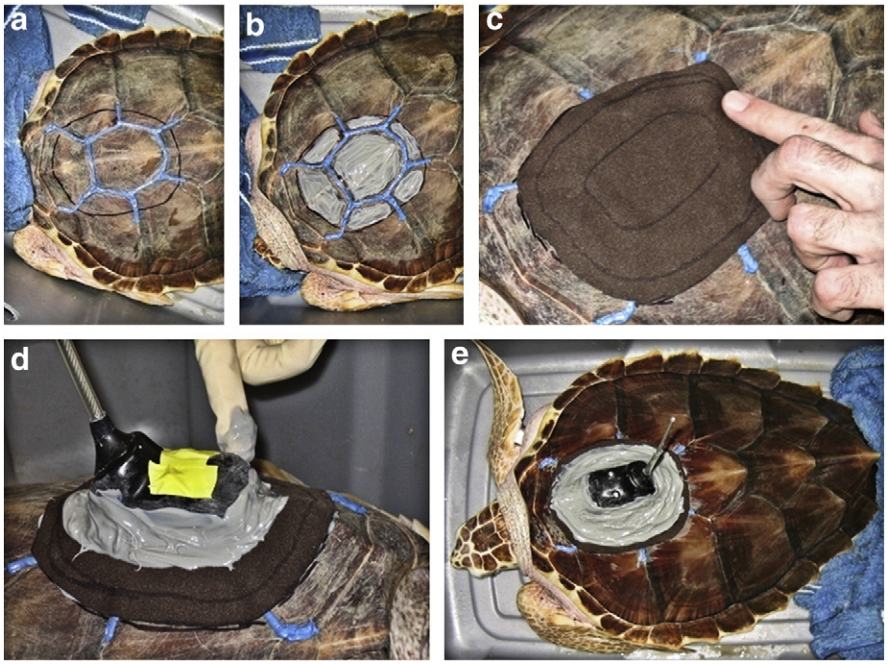


Fig. 1. Neoprene attachment technique. (a) RTV silicone and outline of neoprene attachment site, (b) Power-Fast epoxy on attachment site, (c) attachment of neoprene to carapace, (d) attachment of PTT to neoprene, and (e) completed attachment on captive-reared loggerhead sea turtle.

another research project. Individual growth was plotted for each trial, and average daily growth was estimated using linear regression. Growth rates were compared among the three trials using general linear model analysis of covariance (GLM ANCOVA).

3. Results

3.1. Growth rates

GLM ANCOVA ($F_{2,184}=228.802$, $p<0.001$) indicated that the growth rates of the three different sets of PTT-outfitted loggerheads were significantly different from each other over the course of the three trials.

3.2. Trial 1

Loggerheads in the first attachment trial grew an average of 1.3 cm SCL (SD = 0.5 cm, $n=4$) during 10 January–11 May 2006 (122 d), and all transmitters remained attached when the turtles departed the NOAA STF on Day 134. Upon release into the Panama City pens, one experimental loggerhead was observed rubbing against a piling (BMH, pers. obs.). Both PF-only attachments were shed within 4 h of this observation (Day 135), and one was found at the piling's base. These loggerheads had grown 0.7 and 1.3 cm SCL during 10 January–11 May (Fig. 2a). One PF/SW attachment was shed on Day 146, while the other remained secure until its removal on Day 164. The PF/SW loggerheads grew 2.5 and 1.5 cm SCL, respectively, during 10 January–13 June 2006 (155 d), and linear regression estimated average growth of all four loggerheads as 0.012 cm/d during this time period (Fig. 2a).

3.3. Trial 2

PTT-outfitted loggerheads in the second trial grew an average of 2.3 cm SCL (SD = 0.5 cm, $n=16$, average rate = 0.022 cm/d) during the first 105 d of the trial, and all PTTs were attached when the turtles were placed in the outdoor pens on Day 106. The trial was terminated on Day 134, and all 16 PTTs remained attached, despite increased growth rates in Panama City (0.038 cm/d, Day 105 to Day 134) due, in part, to higher feeding rates. Once removed, the neoprene attachments appeared to have stretched with loggerhead growth (Fig. 3). Overall, the PTT-outfitted individuals grew an average of 3.4 cm SCL (SD = 0.4 cm, $n=16$, Day 0 to Day 134), which was comparable to that of the controls ($\bar{x}\pm 1$ SD = 3.4 ± 0.8 cm, $n=4$, Fig. 2b). Linear regression estimated average growth rate of all loggerheads ($n=20$) and that of all PTT-outfitted individuals ($n=16$) as 0.024 cm/d during the course of the trial (Day 0 to Day 134).

3.4. Trial 3

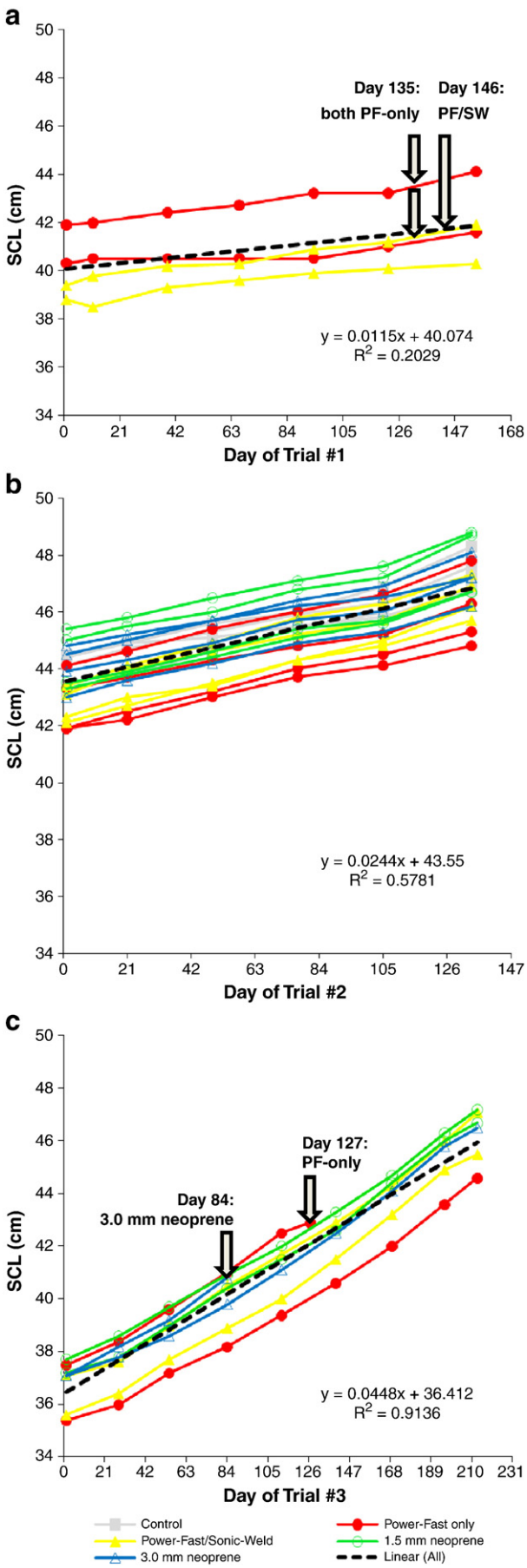
Higher loggerhead growth rates (0.045 cm/d) were recorded in the third trial (Fig. 2c), during which two PTTs were shed (Table 1). Sections of Power-Fast®+ on the perimeter of one 3.0 mm neoprene attachment (TTN261) were observed to have become unattached on 8 October (Day 81), and the PTT fell off on 11 October 2007 (Day 84, 3.7 cm SCL growth). Likewise, gaps were noticed along the perimeter of one PF-only attachment (TTN252) on 1 November (Day 105), and this unit came off on 23 November 2007 (Day 127, 5.4 cm SCL growth). Although no other PTTs fell off during the 213-day trial, gaps occurred along the perimeter of the remaining non-neoprene attachments (beginning on Days 74, 84, and 105, respectively; Fig. 4), and two of the three remaining neoprene attachments became loose or unattached on the edges (beginning on Days 140 and 211), but remained secure in the center (Table 1). The six loggerheads with PTTs still attached on 17 February 2008 (Day 213) grew an average of 9.6 cm (SD = 0.3) during the trial. Four attachments were removed manually with a plastic pry bar within 5 s (PF-only, both PF/SW, 1.5 mm). Removal of the remaining 1.5 and 3.0 mm neoprene attachments took approximately 120 and 30 s, respectively (Table 1).

4. Discussion

4.1. Growth rates

Use of captive-reared loggerheads allowed us to achieve successively higher, significantly different ($p<0.001$) growth rates (SCL)

Please cite this article as: Seney, E.E., et al., Satellite transmitter attachment techniques for small juvenile sea turtles, J. Exp. Mar. Biol. Ecol. (2010), doi:10.1016/j.jembe.2010.01.002



among the trials. The first trial was essentially a pilot study comparing two existing methods, and growth rate was low, providing a baseline for Trials 2 and 3, which had average growth rates roughly double and quadruple that of Trial 1, respectively. The contrasting results between Trials 1 and 2 (3 of 4 PTTs shed vs. none of 16 PTTs shed) indicated that protocol modifications (coarser sandpaper, epoxy discard) improved adhesion of the PF-only and PF/SW methods and justified further examination of the neoprene methods as a less-rigid alternative. Additionally, inclusion of four, PTT-free control turtles in Trial 2 showed no negative impact of PTTs on loggerhead growth rate. Doubling the growth rate again in Trial 3 resulted in transmitter loss, but also highlighted the utility of the neoprene methods under extremely high growth rates as compared to the more rigid attachment protocols. Each of the trials is discussed further below.

4.2. Trial 1

Dummy transmitters in the first attachment trial remained attached to juvenile loggerheads held in a captive environment for over 4 months, but questions remained as to impact of turtle growth and mechanical damage on attachment integrity in the wild. Based on this trial and a separate biofouling trial, attachment techniques were modified during the 2006 field season to include Sonic-Weld® epoxy putty and two antifouling paints (Seney and Landry, 2008). These modifications appeared to improve transmitter life on adult female Kemp's ridleys tracked in the northwestern Gulf of Mexico ($p = 0.05$), but not on juveniles ($p = 0.87$).

4.3. Trial 2

Concerns regarding fast growth rates of juvenile sea turtles prompted efforts to improve adhesion of the epoxy and development of attachment methods incorporating neoprene in 2007. Although loggerheads in the second trial exhibited an average growth rate double that of the first, no PTTs were shed during a 4.5 month period that included a month in outdoor pens. This result suggested that better attachment site preparation and/or discarding potentially unmixed epoxy from the Power-Fast® mixing nozzle improved the PF-only and PF/SW methods as compared to the initial trial and 2004–2006 tracking. Other telemetry projects have undoubtedly recognized the importance of attachment site preparation and proper curing of adhesives, but journals' space restraints may limit reporting of detailed attachment protocols (e.g., Godley et al., 2003; Seney and Landry, 2008; Mansfield et al., 2009). Additionally, the experimental neoprene methods showed promise and merited further examination, given that neoprene attachments performed as well as non-neoprene methods and appeared to have stretched with the turtles' carapaces (Fig. 3).

4.4. Trial 3

Growth of the eight loggerheads in the third attachment trial was accelerated to an average rate nearly four times that of the first. The accelerated growth rate appeared to cause attachment loosening and loss, as well as gaps between the adhesive(s) and carapace. The PF-only and PF/SW attachments sustained 5.4–10.0 cm of SCL growth, but gaps along the edges of these attachments initially became visible on Days 74–105. One PF-only attachment was lost 22 d after gaps appeared, whereas the other three non-neoprene attachments developed significant gaps along their entire perimeters (Fig. 4) and were removed with minimal effort upon termination of the third trial (Table 1). In all likelihood, the three remaining non-neoprene attachments would have been shed much sooner in a natural

Fig. 2. Growth of captive-reared loggerhead sea turtles in (a) Trial 1, (b) Trial 2, and (c) Trial 3. Equations represent the best-fit linear growth function for each trial. Arrows indicate PTT losses.

ARTICLE IN PRESS

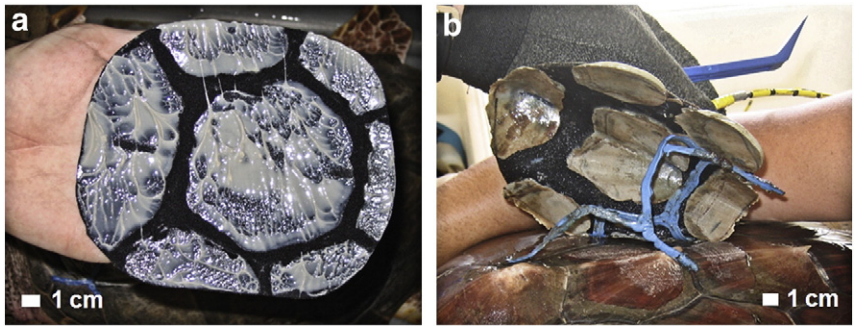


Fig. 3. Epoxy pattern on neoprene removed (a) immediately after attachment and (b) at the end of Trial 2.

environment, where turtles often rub on and/or sleep under hard substrates (Schofield et al., 2006; Frick and McFall, 2007). This may also have been the case for the neoprene attachments, but the results suggest that carefully-applied neoprene attachments have the potential to improve sea turtle track lengths. The neoprene methods successfully stretched and held during substantial carapace growth by three turtles ($\bar{x} \pm 1$ SD = 9.5 ± 0.1 cm). Although the sections of epoxy along the perimeters of two neoprene attachments (Fig. 1b) became loose, the center adhesive remained secure throughout the duration of the trial. Retention of three neoprene attachments suggests that loss of the fourth after only 3.7 cm growth may have occurred due to improper attachment (e.g., epoxy cured along the scute suture line).

4.5. Field deployment

Seven Sirtrack KiwiSat 202 PTTs were deployed on immature Kemp's ridleys in the northwestern Gulf of Mexico during 2007 using the 3.0 mm neoprene/Power-Fast® attachment in tandem with two antifouling paints (Seney, 2008). Battery sensors indicated that all PTTs had sufficient battery power when transmissions ceased, and Argos data gave no indications that any of these ridleys were dead or debilitated. Tracks were comparable, and in many instances longer in duration (11–106 d, $\bar{x} \pm 1$ SD = 54 ± 30 d, $n = 7$), than those recorded in 2004–2006 (12–58 d, $\bar{x} \pm 1$ SD = 38 ± 16 d, $n = 8$), but differences were not statistically significant ($p = 0.20$). Despite this result, long-term trials on captive loggerheads indicated that further development of neoprene attachment methods may be beneficial for tracking smaller, faster-growing sea turtles. Courser sandpaper and epoxy discards were incorporated into the PF/SW method to attach PTTs to adult female Kemp's ridleys in the northwestern Gulf of Mexico since 2007. Six of seven transmitters deployed on nesters in 2007–2008 transmitted for more than a year (Hughes and Landry, unpubl.), indicating the suitability of this method for slower-growing life stages and again highlighting the importance of attachment site preparation and ensuring proper adhesive curing.

Table 1
Summary of Trial 3 results. Transmitter attachment method: Power-Fast® epoxy (PF-only), Power-Fast® and Sonic-Weld® epoxy putty (PF/SW), 1.5 mm neoprene (1.5 mm), and 3.0 mm neoprene (3.0 mm).

Flipper tag	Transmitter attachment method	Day gaps[a] started	Day became loose	Lost or manually removed	Day PTT lost or removed	SCL (cm) increase at time of loss/removal	Removal time (s)
TTN207	PF	84	196	Removed	213	9.2	<5
TTN252	PF	105	–	Lost	127	5.4	N/A
TTN211	PF/SW	74	203	Removed	213	9.9	<5
TTN231	PF/SW	105	213	Removed	213	10.0	<5
TTN216	1.5 mm	–	–	Removed	213	9.5	~120
TTN243	1.5 mm	–	140[b]	Removed	213	9.5	<5
TTN261	3.0 mm	–	81	Lost	84	3.7	N/A
TTN262	3.0 mm	–	211[c]	Removed	213	9.4	~30

[a] See Fig. 4.
[b] All perimeter sections became loose, but the center was still secure on Day 213.
[c] Left and right anterior perimeter sections became loose, but the rest of perimeter and the center were still secure on Day 213.

4.6. Utility of different methods

Growth rates, habitat characteristics, and other factors affecting satellite transmitter retention may differ greatly among species, sub-populations, and life history stages of sea turtles. As such, researchers should consider characteristics of the individual species, geographical region, and size class (SCL) of tracking subjects when selecting an attachment protocol (or protocols). For example, track durations varied substantially (1–945 d, $\bar{x} = 258$ d, SD not reported) among 186 immature loggerheads (25.6–89.1 cm SCL, $\bar{x} = 48.3$ cm, SD not reported) outfitted with PTTs using the Balazs et al. (1996) fiberglass cloth method and subsequently tracked in the Pacific Ocean. The majority of locations for these turtles fell within pelagic regions (Kobayashi et al., 2008), where it likely these turtles grew more slowly (Zug et al., 1995, 1997; Bjorndal et al., 2003) and interacted with considerably less hard substrate than immature Kemp's ridleys in the northwestern Gulf of Mexico. An analysis of track duration vs. SCL was not presented, but both the average SCL and track duration exceed that of the immature ridleys described above. These contrasting results for the same life history stage of different species provide a good example of how transmitter retention can vary among species, life stages, and habitats.

Of the methods tested in our trials, both the PF-only and PF/SW methods are suitable for use on slower-growing life stages and populations; however, Power-Fast®+ was recently discontinued by the manufacturer (see: http://www.powers.com/product_08402.html) and is no longer readily available. Similar products (i.e., two-part epoxies such as Sika AnchorFix®) can be substituted in the PF-only and PF/SW methods, but care should be taken to ensure that curing temperatures are safe for sea turtles, that the curing time is reasonable, and that the bond is secure enough to hold a PTT. The PF-only method has the advantage of requiring the least supplies among our methods; however, it does require application of multiple layers of epoxy to minimize curing temperatures and create a more hydrodynamic shape. The PF/SW method has the added benefit of easily creating a hydrodynamic shape around any PTT. Sonic-Weld® and other steel-reinforced epoxy putties harden quickly (approximately 10 min) and can be easily molded and smoothed after spraying it with soapy water. Application of a layer of Sonic-Weld® over a base of epoxy typically takes less time than building up layers of epoxy around the PTT. Additionally, Sonic-Weld® serves as a rigid barrier around the PTT, affording the PTT some protection if the turtle rubs against hard or abrasive surfaces. Despite their utility for mature and nearly mature sea turtles, neither the PF-only or PF/SW attachment methods are likely to generate long-term tracks from smaller, fast-growing life stages and populations.

Please cite this article as: Seney, E.E., et al., Satellite transmitter attachment techniques for small juvenile sea turtles, J. Exp. Mar. Biol. Ecol. (2010), doi:10.1016/j.jembe.2010.01.002

ARTICLE IN PRESS

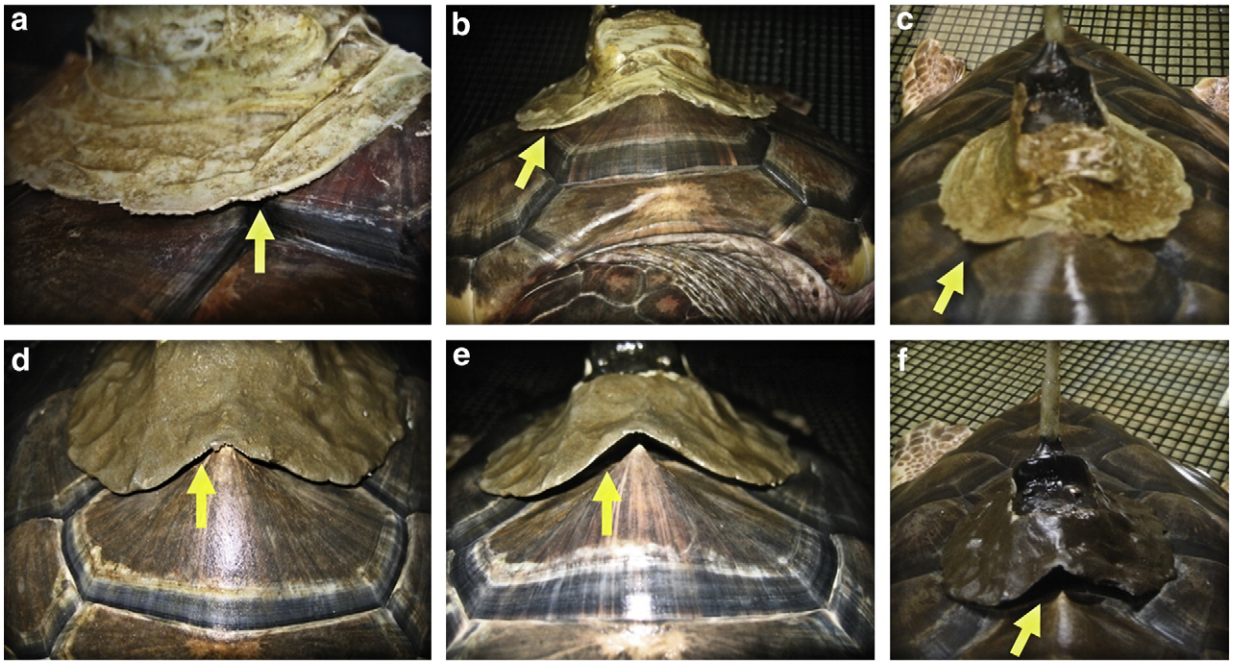


Fig. 4. Trial 3 attachment "gaps." PF-only attachment (TTN207) on Days (a) 83, (b) 104, and (c) 210 (+9.2 cm SCL). PF/SW attachment (TTN211) on Days (d) 76, (e) 126, and (f) 210 (+9.9 cm SCL). Arrow points to same location in each series of images.

The neoprene methods show promise for increasing retention times in turtles with high growth rates, but require more types of materials and a more precise, more time-consuming application to ensure that no epoxy cures along scute suture lines. An added benefit of the neoprene methods is easier application of PTTs to central carapace ridges on small immature sea turtles, such as ridleys and loggerheads. After neoprene has been adhered along the ridge, there is a flatter surface for attachment of the PTT. The neoprene mounts, however, are probably not as durable as a PF-only or PF/SW attachment, and therefore, their utility lies in tracking fast-growing life stages and populations, but not for mature or slower-growing individuals.

5. Recommendations

The trials not only exhibited the potential of PTT attachment techniques incorporating neoprene, but also demonstrated the importance of PTT and carapace preparation and proper mixing of adhesives for maximizing sea turtle track duration. Often attachment techniques are shared informally using verbal or written instructions and/or by having new researchers assist existing programs with a PTT attachment (pers. obs.). While hands-on teaching is valuable for learning such protocols, we recommend that researchers report their protocols in more detail, or separately publish any new "best practices" for a given species, population, or life history stage. We specifically recommend that regions of the carapace and transmitter to which adhesives will be applied should be sanded with very coarse sandpaper (e.g., 60-grit) and thoroughly cleaned (e.g., with acetone) prior to application of any adhesives to increase bonding strength. When utilizing Power-Fast® or another two-part epoxy, the initial "squeezes" from the mixing nozzle should be discarded to ensure proper curing. These steps should be employed for any size sea turtle, whereas a "stretchable" attachment may be useful in acquiring longer tracks from smaller, faster-growing individuals.

The neoprene methods described above should be further investigated to determine their full utility, and improvements should be made as appropriate. Future attachment trials not only should utilize turtles exhibiting high growth rates, but they also should provide natural and/or artificial substrates to determine effectiveness of neoprene and non-neoprene attachments subjected to more "normal" turtle behavior. Likewise, additional sea turtle species should be incorporated into trials, and improvements made to the method as appropriate.

Acknowledgements

Transmitter attachment research was conducted under FWC Turtle Permit #015 issued to Dr. Roger Zimmerman of NOAA Fisheries Galveston. Staff at the NOAA Fisheries Sea Turtle Facility participated in loggerhead husbandry and PTT monitoring. Shanna Kethan is especially acknowledged for her assistance with PTT attachment and photography. NOAA volunteer Robert Morehead was integral to the development of the neoprene attachment method. Kevin Lay of Sirtrack, Ltd. provided initial dummy PTTs and facilitated production of later units. The attachment trials were funded in part by donations to Texas A&M University at Galveston by individuals and through the Seaturtle.org Tracking Adoption Program, and in-kind support was provided by NOAA Fisheries Galveston. Wild Kemp's ridleys were tracked under USFWS Permit TE676379-4 (Zimmerman), NOAA Fisheries Permit 1526 (Landry), Texas Parks and Wildlife Scientific Permit SPR-0390-038 (Landry), and Louisiana Department of Wildlife and Fisheries Scientific Collecting Permit LNHP-05-032 (Landry). EES was supported by a 2008 Texas A&M University Tom Slick Senior Graduate Fellowship during portions of data collection, analyses, and manuscript preparation. Reviewer and editorial comments were valuable for improving the original manuscript. E-mail correspondence with Donald Kobayashi of the NOAA Pacific Islands Fisheries Science Center helped clarify questions regarding Pacific loggerhead tracking. **[SS]**

References

Balazs, G.H., Miya, R.K., Beavers, S.C., 1996. Procedures to attach a satellite transmitter to the carapace of an adult green turtle, *Chelonia mydas*. In: Keinath, J.A., Barnard, D.E., Musick, J.A., Bell, B.A. (Eds.), Proceedings of the 15th Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-37. U.S. Department of Commerce, Miami, Florida, USA, pp. 21–26.

Beavers, S.C., Cassano, E.R., Byles, R.A., 1992. Stuck on turtles: preliminary results from adhesive studies with satellite transmitters. In: Salmon, M., Wyneken, J. (Eds.), Proceedings of the Eleventh Annual Workshop on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFC-302, U.S. Department of Commerce, Miami, Florida, USA, pp. 135–138.

Bjorndal, K.A., Bolten, A.B., Dellinger, T., Delgado, C., Martins, H.R., 2003. Compensatory growth in oceanic loggerhead sea turtles: response to a stochastic environment. Ecology 84, 1237–1249.

Please cite this article as: Seney, E.E., et al., Satellite transmitter attachment techniques for small juvenile sea turtles, J. Exp. Mar. Biol. Ecol. (2010), doi:10.1016/j.jembe.2010.01.002

ARTICLE IN PRESS

Byles, R.A., Keinath, J.A., 1990. Satellite monitoring sea turtles. In: Richardson, T.H., Richardson, J.I., Donnelly, M. (Compilers). Proceedings of the Tenth Annual Workshop on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFC-278, U.S. Department of Commerce, Miami, Florida, USA, pp. 73–75.

Caillouet, C.W., Fontaine, C.T., Manzella-Tirpak, S.A., Williams, T.D., 1995. Growth of headstarted Kemp's ridley sea turtles (*Lepidochelys kempii*) following release. Chelonian Conservation and Biology 1, 231–234.

Chaloupka, M.Y., Musick, J.A., 1997. Age, growth, and population dynamics. In: Lutz, P.L., Musick, J.A. (Eds.), The Biology of Sea Turtles. CRC Press, Boca Raton, Florida, USA, pp. 233–276.

Chaloupka, M., Parker, D., Balazs, G., 2004. Modelling post- release mortality of loggerhead sea turtles exposed to the Hawaii-based pelagic longline fishery. Marine Ecology Progress Series 280, 285–293.

Coyne, M.S., Godley, B.J., 2005. Satellite Tracking and Analysis Tool (STAT): an integrated system for archiving, analyzing and mapping animal tracking data. Marine Ecology Progress Series 301, 1–7.

Frick, M.G., McFall, G., 2007. Self-grooming by loggerhead turtles in Georgia, USA. Marine Turtle Newsletter 118, 15.

Godley, B.J., Lima, E.H.S.M., Åkesson, S., Broderick, A.C., Glen, F., Godfrey, M.H., Luschi, P., Hays, G.C., 2003. Movement patterns of green turtles in Brazilian coastal waters described by satellite tracking and flipper tagging. Marine Ecology Progress Series 253, 279–288.

Godley, B.J., Blumenthal, J.M., Broderick, A.C., Coyne, M.S., Godfrey, M.H., Hawkes, L.A., Witt, M.J., 2008. Satellite tracking of sea turtles: where have we been and where do we go next? Endangered Species Research 4, 3–22.

Hays, G.C., Broderick, A.C., Godley, B.J., Luschi, P., Nichols, W.J., 2003. Satellite telemetry suggests high levels of fishing-induced mortality in marine turtles. Marine Ecology Progress Series 262, 305–309.

Hays, G.C., Broderick, A.C., Godley, B.J., Luschi, P., Nichols, W.J., 2004. Tracking turtles to their death. Marine Ecology Progress Series 283, 299–300.

Hays, G.C., Bradshaw, C.J.A., James, M.C., Lovell, P., Simms, D.W., 2007. Why do Argos satellite tags on marine animals stop transmitting? Journal of Experimental Marine Biology and Ecology 349, 52–60.

Heppell, S.S., Burchfield, P.M., Peña, L.J., 2007. Kemp's ridley recovery: how far have we come, and where are we headed? In: Plotkin, P.T. (Ed.), Biology and Conservation of Ridley Sea Turtles. Johns Hopkins University Press, Baltimore, Maryland, USA, pp. 325–335.

Higgins, B.M., 2003. Sea turtle husbandry. In: Lutz, P.L., Musick, J.A., Wyneken, J. (Eds.), The Biology of Sea Turtles: Vol. II. CRC Press, Boca Raton, Florida, USA, pp. 411–440.

Kobayashi, D.R., Polovina, J.J., Parker, D.M., Kamezaki, N., Cheng, I.-J., Uchida, I., Dutton, P.H., Balazs, G.H., 2008. Pelagic habitat characterization of loggerhead sea turtles, *Caretta caretta*, in the North Pacific Ocean (1997–2006): insights from satellite tag tracking and remotely sensed data. Journal of Experimental Marine Biology and Ecology 356, 96–114.

Mansfield, K.L. 2006. Sources of mortality, movements and behavior of sea turtles in Virginia. Unpublished Ph.D. dissertation, College of William and Mary, Gloucester Point, Virginia, USA.

Mansfield, K.L., Saba, V.S., Keinath, J.A., Musick, J.A., 2009. Satellite tracking reveals a dichotomy in migration strategies among juvenile loggerhead turtles in the Northwest Atlantic. Marine Biology 156, 2555–2570.

Renaud, M., Gitschlag, G., Hale, J., 1993. Retention of imitation satellite transmitters fiberglassed to the carapace of sea turtles. Herpetological Review 24, 94–99.

Schmid, J.R., Witzell, W.N., 1997. Age and growth of wild Kemp's ridley (*Lepidochelys kempi*) turtles: cumulative results of tagging studies in Florida. Chelonian Conservation and Biology 2, 532–537.

Schofield, G., Katselidis, K.A., Dimopoulos, P., Pantis, J.D., Hays, G.C., 2006. Behaviour analysis of the loggerhead sea turtle *Caretta caretta* from direct in-water observation. Endangered Species Research 2, 71–79.

Seney, E.E., 2008. Population dynamics and movements of the Kemp's ridley sea turtle, *Lepidochelys kempii*, in the northwestern Gulf of Mexico. Unpublished. Ph.D. dissertation, Texas A&M University, College Station, Texas, USA.

Seney, E.E., Landry Jr., A.M., 2008. Movements of Kemp's ridley sea turtles nesting on the upper Texas coast: implications for management. Endangered Species Research 4, 73–84.

Snover, M.L., Hohn, A.A., Crowder, L.B., Heppell, S.S., 2007. Age and growth in Kemp's ridley sea turtles: evidence from mark-recapture and skeletochronology. In: Plotkin, P.T. (Ed.), Biology and Conservation of Ridley Sea Turtles. Johns Hopkins University Press, Baltimore, Maryland, USA, pp. 89–105.

Stoneburner, D.L., 1982. Satellite telemetry of loggerhead sea turtle movement in the Georgia Bight. Copeia 1982, 400–408.

Timko, R.E., Kolz, A.L., 1982. Satellite sea turtle tracking. Marine Fisheries Review 44, 19–24.

Troëng, S., Solano, R., Díaz-Merry, A., Ordoñez, J., Taylor, J., Evans, D.R., Godfrey, D., Bagley, D., Ehrhart, L., Eckert, S., 2006. Report on long-term transmitter harness retention by a leatherback turtle. Marine Turtle Newsletter 111, 6–7.

Turtle Expert Working Group, 2000. Assessment update for the Kemp's ridley and loggerhead sea turtle populations in the western north Atlantic. US Department of Commerce, Miami, Florida, USA. NOAA Tech Mem NMFS-SEFSC-444.

Witherington, B.E., 2003. Biological conservation of loggerheads: challenges and opportunities. In: Bolten, A.B., Witherington, B.E. (Eds.), Loggerhead Sea Turtles. Smithsonian Books, Washington, DC, USA, pp. 295–311.

Witzell, W.N., Schmid, J.R., 2004. Immature sea turtles in Gullivan Bay, Ten Thousand Islands, Southwest Florida. Gulf of Mexico Science 2004, 54–61.

Zug, G.R., Balazs, G.H., Wetherall, J.A., 1995. Growth in juvenile loggerhead seaturtles *Caretta caretta* in the north Pacific pelagic habitat. Copeia 1995, 484–487.

Zug, G.R., Kalb, H.J., Luzar, S.J., 1997. Age and growth in wild Kemp's ridley sea turtles *Lepidochelys kempii* from skeletochronological data. Biological Conservation 80, 261–268.

Please cite this article as: Seney, E.E., et al., Satellite transmitter attachment techniques for small juvenile sea turtles, J. Exp. Mar. Biol. Ecol. (2010), doi:10.1016/j.jembe.2010.01.002