Vol. 704: 119–130, 2023
https://doi.org/10.3354/meps14216

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published January 26

Confirmed feasibility of a satellite tracker attachment method on small juvenile hawksbill turtles *Eretmochelys imbricata*

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ABSTRACT: Satellite trackers can be used for studying sea turtle movement, illuminating their migrations and behaviours. However, many studies have focused on adult turtles, with uneven species representation, despite the importance of understanding movement and habitat use of turtles at all life-stages. Furthermore, few publications detail successful satellite tracker attachment methods, particularly for juveniles. Smaller-sized juvenile sea turtles often have an irregularly shaped carapace and are fast growing, rendering the attachment of rigid trackers in a safe and durable manner challenging. Juvenile hawksbill turtles' specific carapace shape and imbricated scute arrangement further complicate satellite tracker attachment compared to juveniles of other turtle species. This study's objective was to confirm the feasibility of an attachment method that would allow small-sized juvenile hawksbill turtles (~267–345 mm curved carapace length) to continue growing, without tracker loss or damage to underlying scutes. Replica trackers were made of resin (simulating Wildlife Computer Spot-387 trackers), and attached with epoxy, silicone and neoprene, using a technique modified from those used on neonate loggerheads and Kemp's ridleys. Throughout the study (3.5 mo), replica trackers remained attached, the turtles grew up to 114% heavier and 25% longer, and all turtles appeared clinically healthy and active. Furthermore, all scutes were undamaged after tracker removal. As a critically endangered species, the paucity of data on hawksbill turtles, and specifically juveniles, can hinder evidence-based management decision-making. The improved ability to satellite track juvenile hawksbills can, therefore, help better our understanding of their ecology and inform management and conservation practices for this species.

KEY WORDS: *Eretmochelys imbricata* · Sea turtle · Satellite tracking · Attachment methodology · Remote sensing

1. INTRODUCTION

Conservation of sea turtles requires an understanding of their ecology to develop effective management measures (Rees et al. 2016, Levy et al. 2017, Yeh et al. 2021). Sea turtle behaviour is specific to each life-stage (Bolten 2003, Mansfield et al. 2014, 2021) and species (Plotkin et al. 2002), necessitating the study of every species, at each life-stage, and often in different regions. Yet, because

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the non-uniformity of threats in space and time across the range of the species is not evenly represented in the literature, there have been several studies advocating for expanded research in understudied species and age classes (Godley at al. 2008, Hazen et al. 2012). Sea turtle habitat usage and behaviour are often inferred via platform-based observations or telemetry data (Horrocks et al. 2001, Hart et al. 2012, Hays & Hawkes, 2018, Robinson et al. 2020). Satellite tracking is one of the most commonly used techniques; however, published sea turtle satellite tracking studies have predominantly focused on adult-sized turtles, primarily loggerheads *Caretta caretta* and green turtles *Chelonia mydas* (Godley et al. 2008). While the methods for attaching satellite tags to adult-sized turtles are well established (Balazs et al. 1996), published studies often lack detail on the tracker attachment method and do not specify whether any methodological amendments were made to account for species or life-stage differences. Recently, there has been an increase in studies tracking smaller size classes of marine turtles and investigating more appropriate attachment methods and tracker types based on turtle life-stage (Pabón-Aldana et al. 2012, Mansfield et al. 2014, 2017, 2021, Putman & Mansfield 2015). This expansion of research is important because optimising a safe and durable satellite tracker attachment method for all sea turtles, specific to species and size-class, would help improve tracking outcomes and help clarify ontogenic movement patterns and foraging ground usage.

Sea turtles have different diets, habitats, growth rates, and morphology throughout their development (Bolten et al. 2003). These distinctive characteristics define the life-stage of the turtle, and for immature turtles, they generally correlate with turtle size (Van Buskirk & Crowder 1994). There is some consensus on the approaches used to determine the minimum size of maturity, with variation between and within species (Bjorndal et al. 2014, Phillips et al. 2021). However, the term 'juvenile turtles' is more subjective and has been used to refer to many different stages of immature turtles (Morafka et al. 2000), including dispersal stage turtles (neonates, i.e. those in their first year of life; or post-hatchlings, i.e. offshore oceanic stage) and post-dispersal stage turtles recently transitioned to neritic foraging habitats (new recruits), and sub-adults (Crouse et al. 1987, Bolten 2003).

One key difference influencing the choice of satellite tracker attachment method in juvenile hard-shelled turtles compared to adult-sized turtles is variation in carapace morphology (Wyneken 2001). The standard method of attachment for hard-shelled turtles, based on Balazs et al. (1996) is a direct attachment of the satellite tracker to the keratinised carapace scute using an epoxy-based adhesive, with or without strips of fibreglass for extra stability. However, this method is difficult to use in juvenile turtles because (1) the base area of the tracker can be larger than the scute size; (2) the carapace morphology of smaller-sized juvenile turtles, such as post-hatchlings, is such that they often have a raised ridge of vertebral scutes (Mansfield et al. 2012); and (3) juvenile turtles are still growing, and growth can affect tracker retention. Furthermore, this epoxy-based method is unsuitable for use on other species such as leatherback turtles *Dermochelys coriacea*, or flatback turtles *Natator depressus* (Sperling & Guinea 2004, Fossette et al. 2008).

Attaching satellite trackers to small-sized juvenile turtles such as dispersal stage or those recent recruits to neritic habitats presents a further issue. Although smaller and lighter satellite trackers have been developed, attachment methods need to account for the accelerated growth rate in these earlier life-stages compared with later ones (Bellini et al. 2019). Attachment techniques developed for adult turtles use hard epoxies, which if used on juvenile turtles could inhibit growth rates, hence a requirement for some level of flexibility in the attachment method has been identified (Seney et al. 2010, Mansfield et al. 2012). Furthermore, if an attached tracker spans multiple scutes, traditional direct attachment methods could jeopardise scute growth and shape since scutes grow marginally (Wyneken 2001). Additional challenges relate to carapace morphology: (1) Oceanic dispersal stage loggerhead and Kemp's ridley *Lepidochelys kempii* turtles and new recruit (post-dispersal) hawksbill *Eretmochelys imbricata* have a distinct vertebral ridge running the length of the carapace (Fig. S1a in the Supplement at www.int-res.com/articles/suppl/m704p119_supp.pdf). (2) In juvenile hawksbill turtles the carapace is uniquely formed of overlapping scutes (Salmon et al. 2018), which are slightly raised at the trailing edge (Fig. S1c), and the first vertebral scute may be convex (authors' pers. obs.; Fig. S1b). Consequently, the uneven surface of their carapace reduces the available flat surface area for best contact with the satellite tracker. To counter this, a high volume of epoxy would be required to build a flat area, adding weight, height, and surface area to the attachment site, as well as producing extra heat during epoxy curing. Thus, tracker attachment techniques for smaller-sized juvenile turtles require testing to develop techniques that minimize potential shell damage and do not impede growth or cause negative behavioural changes (Mansfield et al. 2014, 2017, 2021, Putman & Mansfield 2015).

The challenge of attaching satellite trackers to smaller-sized juvenile hawksbills is similar to those when designing techniques to track juvenile loggerhead and green turtles as well as oceanic-stage Kemp's ridley turtles (Seney & Landry 2011). The published methods of satellite tracker attachment for these species found that the optimal techniques differed between green and loggerhead turtles (Mansfield et al. 2021), and both techniques (Seney et al. 2010, Mansfield et al. 2012) could be used as a starting point to explore options for attachment to smaller-sized juvenile hawksbills. For example, Mansfield et al. (2012) tested 4 direct attachment methods and 2 indirect attachment methods for solar satellite trackers on neonate loggerhead turtles (12–25 cm straight carapace length [SCL]). They concluded that both indirect attachment methods used on the neonate loggerhead turtles were deemed unsuitable as they restricted normal growth (Mansfield et al. 2012) and it would be reasonable to assume the same problem would occur if these methods were used to attach tags to similarly sized juvenile hawksbill turtles. From Mansfield et al.'s (2012) study, the method that yielded the best adhesion over time for loggerheads used a neoprene-silicone attachment on an acrylic base coat. This method of attachment was also thought to mitigate the challenge of carapace unevenness in juvenile hawksbill turtles and enable longer attachments.

A technique by Seney et al. (2010) used a combination of epoxy-based adhesive and a neoprene base to allow for the growth of new recruit-sized juvenile loggerhead turtles. This method could be transferable to comparably sized juvenile hawksbill turtles; however, the unique scute morphology of juvenile hawksbill turtles necessitates validation of the method as some modifications may be required to reduce the development of perimeter gaps between the neoprene and carapace (Seney et al. 2010) and enable longer attachment duration. Hence the aim of this study was to optimise and test the Seney et al. (2010) protocol for the attachment of satellite trackers to small-sized juvenile hawksbill turtles (similar in size to new recruits from the same population) by confirming that trackers remained firmly attached for more than 3 mo and caused minimal scute damage or disfigurement after tracker removal.

2. MATERIALS AND METHODS

2.1. Study animals

Eleven hawksbill turtle hatchlings were collected from Milman Islet, Queensland, Australia (11.167° S, 143.017° E) on 17 March 2019 with authorisation from the Department of Environment and Science (Permit reference: WA0012830). Hatchlings emerged naturally from 1 nest and were allowed to run the course of the beach but were collected before entering the water. The hatchlings were transported to James Cook University (JCU), Townsville, Australia, and raised in a purpose-built facility following the facility's husbandry manual and standard operating procedures (WLD-16) under JCU Animal Ethics permit A2586. Turtles were housed individually in open-air, recirculating seawater systems. The water was filtered under a 40 W UV bulb and maintained at seasonal temperatures ranging from 25 to 30°C to reflect natural temperature variation on the Great Barrier Reef (Lough 1998). Prior to the commencement of the trials, the turtles in this study weighed between 1990 and 3890 g (median 2940 g; IQR 2467.5–3265 g) and had a curved carapace length (CCL) of 267–345 mm (median 314 mm; IQR 297–328 mm). For comparison, in Queensland, the size range of hawksbill turtles classed as new recruits to the foraging habitats is 322 to 418 mm CCL (Limpus 1992, Limpus et al. 2008), hence classifying them as small juveniles (Robinson et al. 2021).

2.2. Turtle diet and growth observations

Throughout the study, the turtles were fed a blend of human-grade whole fish, fish fillets, mixed vegetables, and gelatine, combined with vitamins and solidified into cubes for consumption. Turtles were fed between 3 and 5% of their body weight on weekdays, with the aim of all turtles weighing at least 5 kg by release. Growth was measured as an indicator of welfare rather than for a specific growth study so individual feed amount was not considered critical. Turtles were weighed every 1–2 wk throughout the study to ensure continuous growth and adjust feed quantities accordingly. Daily observations of the turtles were noted for welfare monitoring, and weekly checks of the trackers were also recorded throughout the study to look for signs of tracker dislodgement or formation of perimeter gaps in the neoprene. If the trackers had detached during the 3 mo test period (per the study objective), or turtle behaviour indicated reduced welfare, this attachment methodology would have been discontinued and rejected. Turtles were measured periodically from when they arrived at the JCU facility to when the trial commenced. Turtles could not have CCL measured whilst replica trackers were attached, but CCL was measured again at the end of the trial period after replica tracker removal. SCL was not recorded during this experiment. We applied a linear mixed effect model with treatment, and a random intercept of individual turtle ID, to turtle growth data from 17 March 2020 to the date of replica tracker attachment to predict turtle growth rates for the period of tracker attachment (CCL in mm d^{-1}). Data were modelled using R 4.1.1 (R Core Team 2021), with tidyverse (Wickham et al. 2019) and lubridate (Grolemund & Wickham 2011) packages in RStudio 1.4.1717 (RStudio Team 2021).

2.3. Replica tracker attachment

Replica trackers modelled after genuine satellite trackers were constructed and used in this proof-of-concept study. Protite Clear Casting and Embedding Resin and a metal wire antenna were used to create replica trackers matching the approximate shape, dimensions, and weight of the SPOT-387 satellite tracker produced by Wildlife Computers (59 × 29 × 23 mm, 39 g) (Fig. 1). One turtle, the heaviest at the time, had its replica tracker attached on 2 November 2020. The remainder were attached on 27 November 2020 (n = 6) and 28 November 2020 (n = 4).

2.3.1. Carapace preparation prior to attachment

The turtles were scrubbed with a toothbrush and fresh water 2 d prior to tracker attachment to reduce the time spent cleaning on the day of attachment. The first 3 vertebral scutes and first 2 pairs of costal scutes were ‘flossed’ using a thin damp cloth to remove algae and other debris accumulated under the overlapping scutes (Fig. 2a). On tracker attachment day, each turtle was dried and then weighed (g) and measured (± 1 mm CCL). After weighing, turtles were placed on top of a clean towel on a table and held in place by one person who kept the turtles’ eyes covered (Fig. 2b) while a second person prepared the carapace and attached the trial tracker.

Sandpaper (60-grit, as per Seney et al. 2010) was used on top of the first 3 vertebral scutes and the first 2 pairs of lateral scutes of the carapace and underneath overlapping scute edges to remove algal biofilm and to assist with successful adhesion (Fig. 2c). Sanding always occurred uni-directionally to limit damage to the brittle scute edges. After sanding, the carapace was wiped in a craniocaudal direction with fresh water and a cloth. The gaps underneath the scutes were also cleaned by syringing freshwater (Fig. 2d), wiping with a thin cloth and using a toothpick to remove as much biofilm as possible (Fig. 2e). This process of sanding and washing with freshwater was repeated 3 times to ensure the carapace was as clean as possible. Following this cleaning protocol, the first 2 vertebral scutes and the first 2 pairs of costal scutes were scored superficially with a serrated knife to create additional surface area for the neoprene and epoxy to grip (Fig. 2f). A new cloth was then used to wipe down the carapace with acetone (Seney et al. 2010), and the gaps underneath the scutes were also syringed and flossed with acetone one final time and air dried in preparation for epoxy application.

2.3.2. Neoprene and tracker attachment

In this study, 3 mm neoprene was selected as it was comparable to other studies (Seney et al. 2010), thick enough to help level the uneven surface of the scutes and vertebral ridge, and presumably flexible enough to allow turtle growth without tracker loss. Prior to carapace preparation, neoprene was prepared

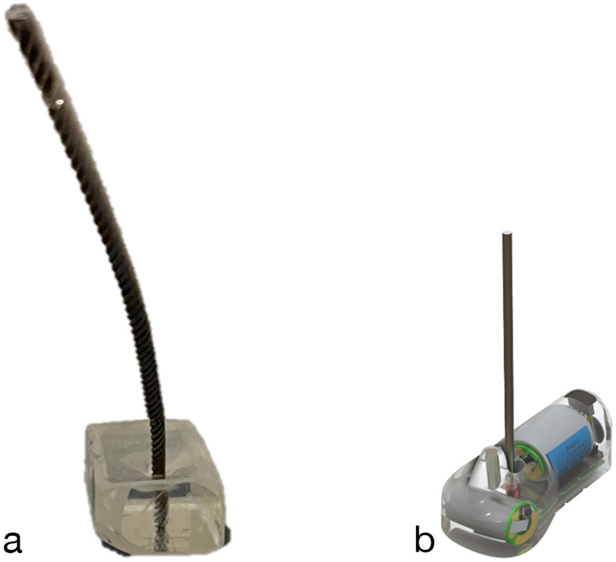

Fig. 1. Comparison of (a) replica tracker used in this study; and (b) SPOT-387 satellite tracker manufactured by Wildlife Computers (tracker dimensions 59 × 29 × 23 mm, 39 g)

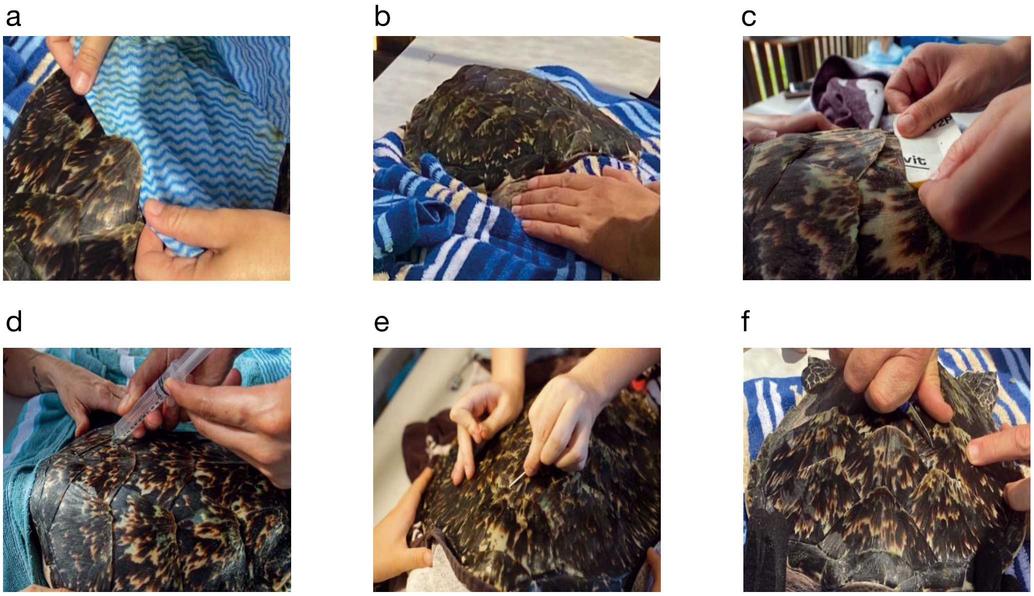

Fig. 2. Preparation of juvenile hawksbill turtle carapace for neoprene and satellite tracker attachment. (a) Using an absorbent cloth to 'floss' underneath scutes; (b) covering turtle's eyes to keep it calm during carapace preparations; (c) using 60-grit sandpaper to sand underneath overlapping scutes; (d) using a syringe filled with fresh water to clean underneath overlapping scutes; (e) removing biofilm from underneath overlapping scutes with a toothpick; (f) using a serrated pocket knife to score scutes in preparation for neoprene attachment

by soaking in a double cycle of bleach bath (liquid chlorine as sodium hypochlorite) for 1 h and then overnight in fresh water to disinfect the neoprene and remove any grit. Neoprene size and shape (approximately 15 × 15 cm, with rounded edges) were adjusted for each turtle individually to ensure complete coverage of the second vertebral scute and partial coverage of the surrounding 6 scutes (Fig. 3a). The silicone used was Sikasil® Pool as it is water, UV, weathering and fungal resistant and has high elastic-

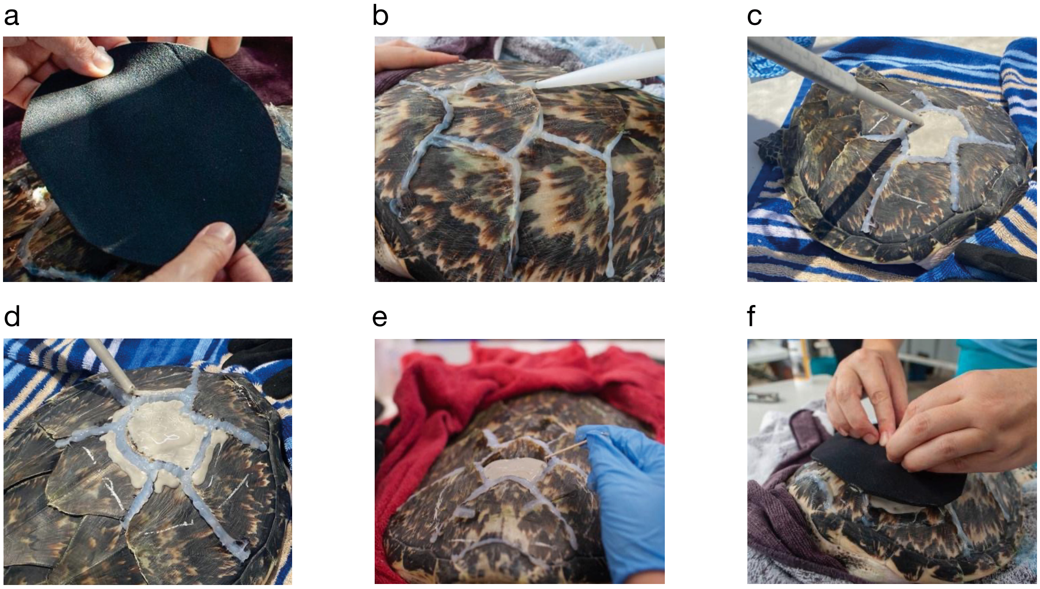

Fig. 3. Lining juvenile hawksbill turtle scutes with silicone and attaching the neoprene with epoxy. (a) Round shape of neoprene patch, cut to fit individual turtles; (b) silicone barrier being created underneath the scutes to allow for unrestricted growth; (c) applying epoxy to the first scute according to the attachment process; (d) applying epoxy to surrounding scutes; (e) using a toothpick or gloved finger to remove air bubbles from applied epoxy; (f) neoprene patch being first applied in the centre and then pressed down in an outward direction

ity. Silicone was prepared by discarding the volume contained within the neck of the tube and was then applied to the carapace. It was used to fill gaps under the raised scutes, ensuring that there was also a visible line of silicone along all scute edges that would be covered by the neoprene (Fig. 3b). The silicone was smoothed and flattened to ensure complete contact with the scutes, especially as some gaps started to form when the silicone was setting. Therefore, more silicone was added to fill any gaps that formed during drying. When the silicone was touch dry, the next phase of neoprene attachment was initiated.

The epoxy used was Sika AnchorFix®-3+ as it is one of the fixatives commonly used by researchers for satellite tracker attachment on hard-shelled turtles (Shimada et al. 2012, 2016). Epoxy was prepared the same way as the silicone, by discarding a small amount before applying a thin layer to cover the second vertebral scute. This area was subsequently built up to flatten out the raised curve created by the first vertebral scute (Fig. 3c). Epoxy was also applied to the surrounding scutes that would be covered by neoprene, starting from the silicone lining the second vertebral scute and working outwards towards the marginal scutes (Fig. 3d). Care was taken not to allow bubbles to form in the epoxy, as this would reduce adhesion. Epoxy was smoothed, and bubbles were removed by hand or by using a toothpick (Fig. 3e). Epoxy was applied up to the silicone edges but not atop. The epoxy was allowed to dry until it had a tacky consistency before applying the neoprene. To attach the neoprene, some pressure was applied by hand to the centre and worked concentrically and outwardly to remove air bubbles. The neoprene was held firmly in place for a few minutes to ensure complete contact with the adhesive to the carapace (Fig. 3f).

After the neoprene was secured, a silicone barrier was created, outlining where the tracker would be attached (Fig. 4a). Epoxy was applied to the underside of the tracker (Fig. 4b), which was then directly applied close to the top edge of the neoprene. Additional epoxy was added around each edge of the trial tracker and up the sides of the tracker to ensure good adhesion to the neoprene. The silicone barrier assisted with the epoxy build-up (Fig. 4c). The epoxy was allowed to cure for at least an hour before a final ring of silicone was added to the edge of the neoprene (Fig. 4d) to act as an additional barrier to algal growth under the neoprene. Turtles were kept dry-docked in individual containers for 12 h to allow the epoxy to cure, each on a towel dampened with saltwater to prevent dehydration. Flippers were tucked at the side of the carapace and covered by a towel to prevent the animals from knocking the trial trackers or getting epoxy on their flippers during the epoxy drying time. Turtles were also monitored throughout the process for signs of distress, such as rapid flipper movement, and calmed by gently covering their eyes. Antifoulant is usually painted onto satellite trackers before deployment to reduce algal growth; however, due to potential toxicity (Amara et al. 2018), it was not applied in the trial setting of recirculated seawater. This is also why the 12 h curing time was adhered to in this experiment. However, using the same epoxy in the field setting, it would be possible to release the turtles back into the ocean after a shorter time (approximately 6–8 h) if overnight containment was not possible (E.A., M.H., I.B., K.J., J.G. pers. obs.).

2.4. Replica tracker removal

As all trackers remained firmly attached at the end of the trial, the first replica tracker was intentionally removed on 1 March 2021, approximately 4 mo after the attachment. The remaining replica trackers were removed over 4 d (11, 12, 16, and 17 March 2021), approximately 3.5 mo after attachment. Removal of trackers occurred approximately 1.5 mo before attaching the genuine Wildlife Computers SPOT 387

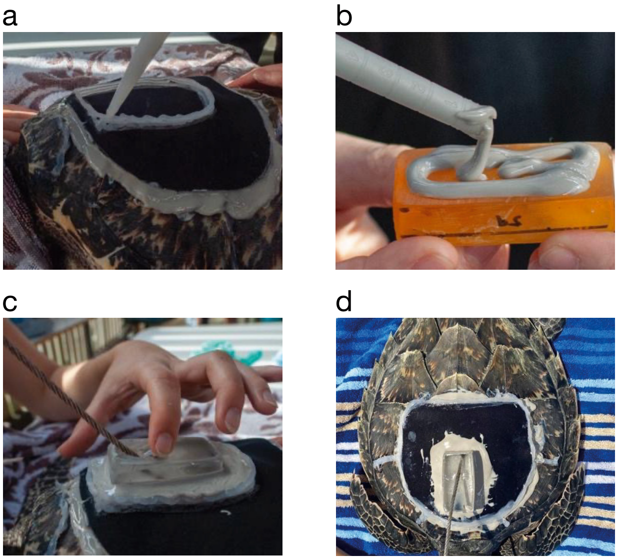

Fig. 4. Tracker attachment to neoprene and final silicone seal added around the edge of the neoprene. (a) Creating a silicone dam to assist with epoxy build-up around the sides of the tracker; (b) epoxy applied directly to the bottom of the trial tracker; (c) positioning the tracker inside the silicone dam; (d) final silicone layer added to the edge of the neoprene

satellite trackers for a subsequent dispersal study. Turtles were first dried, weighed and photographed before tracker removal. After tracker removal, they were measured (CCL), photographed, and reweighed.

3. RESULTS

Replica satellite trackers were successfully attached to 11 small juvenile hawksbill turtles (267 to 345 mm CCL). The first attachment was undertaken initially to test and confirm the attachment method and the remaining 10 trackers were attached within 1 d of each other. The attachment process took approximately 1–1.5 h per turtle, excluding curing time and pre-cleaning. The total in-air weight of the tracker (39 g to replicate the SPOT-387 trackers), plus the epoxy, silicone and damp neoprene, was 4.5–7.8 % of turtle body weight at the start of the trial and 2.5–3.9 % of turtle body weight at the end of the trial (average ± SE tracker and attachment material weight was 162.0 ± 4.42 g).

3.1. Attachment success

All trial trackers remained firmly attached with no evidence of neoprene peeling from the carapace or the tracker from the neoprene for at least 3 mo, meeting our objective. Algae was found on the tracker and neoprene (Fig. 5a), but this had no noticeable effect on the adhesion. On removal of the replica trackers, the carapace scutes under the replica trackers were undamaged (Fig. 5b); however, the neoprene attached to the replica trackers had to be removed in pieces. Therefore, it was not possible to compare our results with the photograph of the neoprene used in the Seney et al. (2010) study.

3.2. Growth of turtles during trial

Total weight gained throughout the experiment ranged from 1640 g to 2980 g, and CCL growth ranged from 50 mm to 94 mm (Fig. 6). Median weight gain and CCL growth across all 11 turtles was 2230 g (IQR 1995–2595 g) and 56 mm (IQR 52–63 mm), respectively. The weight gain per turtle from start to end of the study ranged from 67 % body weight increase to 114 % body weight increase (median 76 %, IQR 72–84 %). The CCL growth per turtle from the start to the end of the study ranged from a 14 % increase to a 28 % increase (median 18 %, IQR 17–22 %) (Table S1 in the Supplement). Repeated measurements indicated a steady CCL increase (Fig. 7) and weight gain throughout the trial (Fig. S2 in the Supplement) in accordance with each individual turtle's growth trajectory prior to the study. There was no statistical difference between the calculated daily growth (CCL in mm d^{-1}) of turtles before the replica trackers were attached and after the replica trackers were removed ($t_1 = -1.674$, $p = 0.096$).

When comparing the calculated daily growth rate of the turtles during the trial (weight or CCL gained divided by the number of days in the trial), there was a median increase of 20.9 g d^{-1} (IQR 19.4–24.0 g) and 0.5 mm d^{-1} (IQR 0.5–0.6 mm) weight and CCL, respectively. Calculated daily turtle growth rates ranged from 15.2 to 25.4 g d^{-1} in weight gain and 0.5 to 0.8 mm d^{-1} in CCL increase. The calculated annual growth rate of the turtles in this trial from 1 yr old to 2 yr old averaged 228.4 mm yr^{-1} in CCL, including the attachment trial period.

4. DISCUSSION

This study confirmed the feasibility of a method for satellite tracker attachment to small juvenile hawksbill turtles that were a similar size to new recruit turtles beginning to forage in benthic neritic areas (Velez-Zuazo et al. 2008). Furthermore, this attachment method did not result in tracker detachment, damage to scutes, or short-term reduction of growth within the 3–4 mo study period. This is the first known study to test a tracker attachment method for any size of juvenile hawksbills, so there are no comparable data in the published literature. Whiting & Koch (2006) reported the outcome of a single juvenile

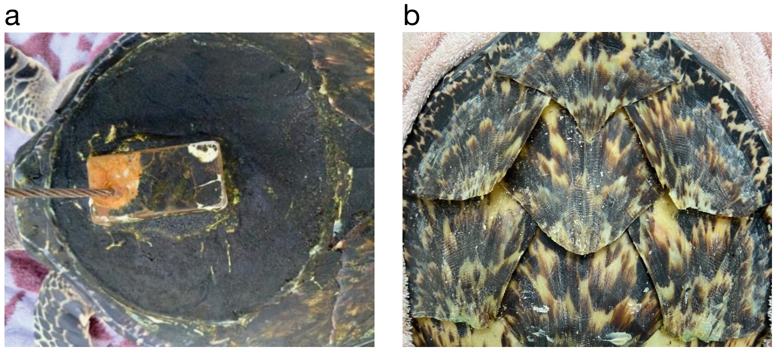

Fig. 5. (a) Algal build-up on neoprene and replica tracker at the end of the study; and (b) undamaged scutes with minimal algal build-up, photographed directly after removal of replica tracker

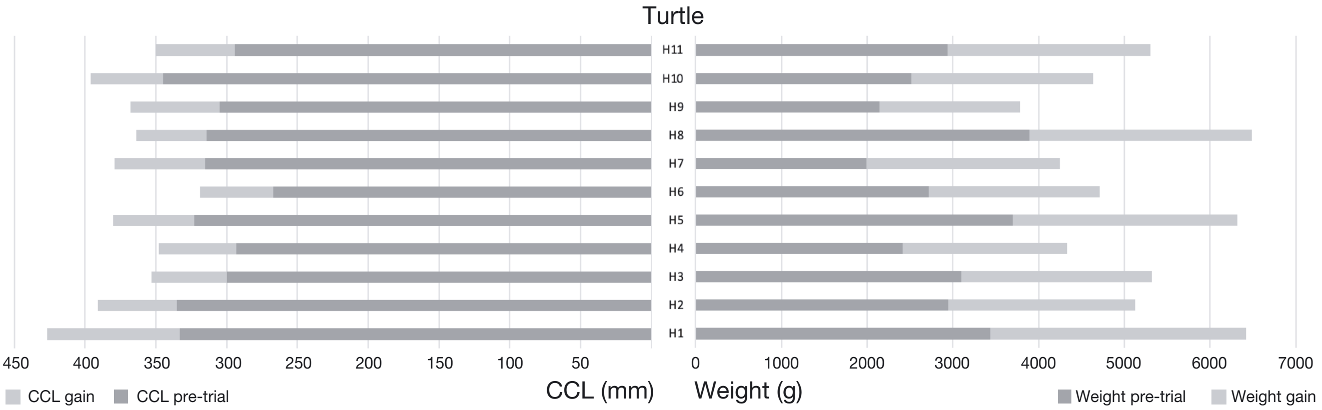

Fig. 6. Curved carapace length (CCL) and weight of each juvenile hawksbill turtle pre- and post-trial. Dark and light grey bars collectively indicate each turtle's total weight or CCL at the end of the trial

hawksbill turtle that was satellite tracked from the Cocos (Keeling) Islands, but no attachment methodology was described. Similarly, other studies have satellite-tracked juvenile hawksbill turtles, but without detailing whether any adaptations from the techniques commonly used on adult turtles were used to fit trackers to juvenile hawksbill carapaces (Martinez-Estevez et al. 2021, Robinson et al. 2021).

4.1. Attachment success

Although the hawksbills were housed in a clean environment, the exposure to natural light enabled some algal build-up on the neoprene and replica trackers. The turtles were routinely scrubbed throughout the trial, as per in-house husbandry procedures; however, any algae on the neoprene and trackers were not removed. Algal growth is an issue for satellite tracking as it can inhibit the functioning of the sensors, thus preventing the upload of data from the trackers to the satellite system (Hays et al. 2007), and algal growth under the tracker can cause it to become detached. Without application of antifoulant, there was algal growth on the neoprene and trial trackers; however, there was no evidence of the neoprene peeling, as noted by Seney et al. (2010). In our trial, the additional silicone seal applied around the edge of the neoprene likely helped prevent the peeling of the neoprene and algal growth underneath it.

The use of neoprene for the attachment of satellite trackers to small juvenile turtles has been documented by Mansfield et al. (2012) to accommodate the vertebral ridge and by Seney et al. (2010) to allow for shell growth. Both benefits of using neoprene to attach trackers to the juvenile turtles in this study were noted. Primarily, neoprene provided the flexibility needed to account for accelerated growth in this size

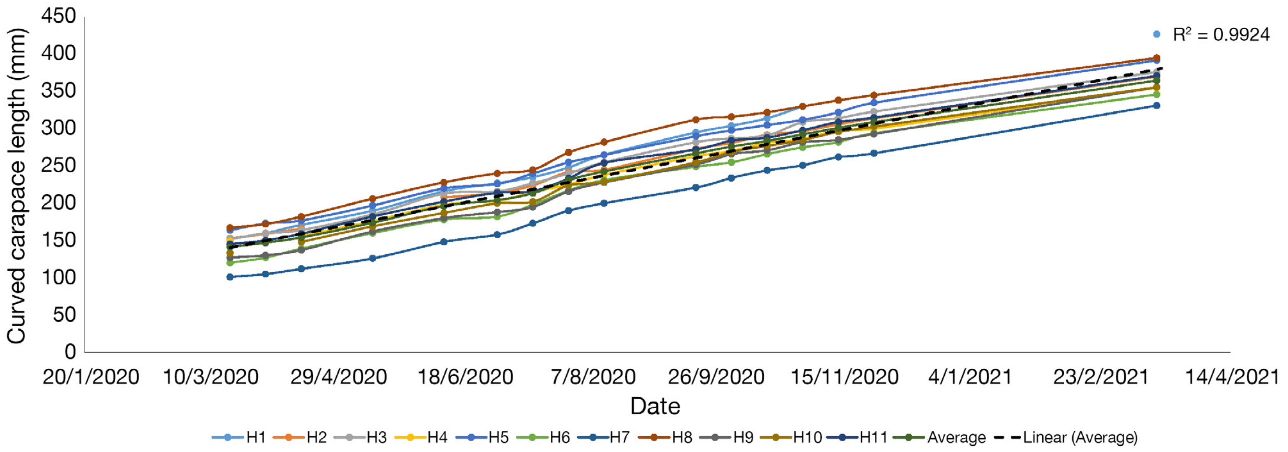

Fig. 7. Curved carapace length (CCL) increase of the 11 hawksbill turtles (Turtle ID 1–11) from March 2020 (1 yr old) to March 2021 (2 yr old). No CCL measurements were taken during the trial period with replica trackers attached (November 2020–March 2021). Red line: linear regression of averaged turtle CCL over time; black dashed line: linear regression of averaged turtle CCL over time

class that could otherwise cause trackers to fall off prematurely or cause malformation of the carapace (Seney et al. 2010). Similar to loggerhead turtles, juvenile hawksbills have reduced attachment points on their carapaces due to the ridged shape and small size of their scutes. Neoprene can provide an anchor point across multiple scutes, whereby the additional thickness helps to create a flatter surface for adhesion, and the flexibility of the layers allows for carapace growth. Seney et al. (2010) compared different thicknesses of neoprene without indicating any preference in the results. In our trial, 3 mm neoprene was found to be thick enough to account for the unevenness of the carapace whilst being flexible enough to accommodate growth. Furthermore, this study used neoprene patches that were larger than previous studies and shaped to cover the most cranial 7 scutes of the carapace to maximise surface area for adhesion. The continued development of smaller trackers could eventually make the need for neoprene redundant; however, the likely size of a tag to fit one scute would be difficult to specify as the size and shape of scutes can vary greatly between individuals. Moreover, the 'bumpiness' of the individual scutes (Salmon et al. 2018) prevents a tracker from sitting well on just one scute alone; hence previous tracking studies have often targeted larger juveniles (Hays et al. 2021) to which the tracker could be attached more easily.

Sanding or scoring of the carapace is common during satellite tracker attachment (Balazs et al. 1996), presumably to reduce the biofilm and increase surface area for better adhesion and longevity of tracker attachment (Hoffman 2020). However, detailed assessments of potential scute damage post-tracker removal are lacking in the literature. This study found that sanding and scoring were not evident after replica tracker removal 3–4 mo later, indicating no long-term physical damage from this procedure. Additionally, in terms of welfare, the turtles in our trial had been handled and gently scrubbed as part of weekly husbandry since being at the research facility. This process may have helped reduce their stress, as they did not display signs of discomfort such as hyperactivity or rapid body movement (Arena et al. 2014) during sanding, acetone wash or epoxy application, or over the following few days.

4.2. Growth of turtles during trial

Calculated growth rate estimates of wild hawksbill populations vary between regions but there is consensus in the literature that hawksbill growth rates differ by age and are highest in juvenile turtles (Chaloupka & Limpus 1997, Bell & Pike 2012, Snover et al. 2013, Bellini et al. 2019). In our study, the turtles followed a linear growth pattern and grew throughout the trial without detectable damage to, or misshaping of, the underlying scutes as noted for the hard attachment methods studied in Mansfield et al. (2012). This could be attributed to the silicone that was applied to the edges of the underlying scutes, as Seney et al. (2010) indicated that the silicone could provide the necessary flexibility for scute growth. It should be noted, however, that the turtles observed by Mansfield et al. (2012) were much smaller than those in this study or Seney et al. (2010). In comparison with annual growth estimates of wild juvenile hawksbill populations (33–108 mm yr^{-1} CCL), the captive-raised animals used in our study had a higher growth rate (Limpus 1992, Boulon 1994, Gutiérrez Montero & Pena 1996, Chaloupka & Limpus 1997, León & Diez 1999, Diez & van Dam 2002, Blumenthal et al. 2009, Bjorndal & Bolten 2010, Krueger et al. 2011, Hart et al. 2013, Wood et al. 2013, Hawkes et al. 2014, Bjorndal et al. 2016, Van Houtan et al. 2016, Llamas et al. 2017, Bellini et al. 2019, Santos et al. 2019, Cañas-Uribe et al. 2020, Avens et al. 2021), which is a common outcome of captive-reared turtles. Thus, our technique should be applicable to slower-growing wild turtles (Bjorndal & Bolten 2010, Bjorndal et al. 2016). Since all study turtles were from the same clutch, they may have genetically inherited high growth rates (Heppell et al. 2002). However, there was also individual variation in growth between study turtles.

4.3. Limitations of study

Although this study validated the described tracker attachment method, the attachment duration and lack of a control group are limitations to consider when interpreting our results. The study animals were scheduled to be released into the wild in early May 2021, fitted with genuine Wildlife Computers Spot-387 trackers; therefore, trial trackers were deliberately removed prior to this. Although we could not determine maximum attachment time by allowing natural detachment of the trackers, our replica trackers remained intact for 3.5 to 4 mo, with no noticeable adverse effects to the turtles. Given that Spot-387 trackers have an expected battery life of 5 to 6 mo, the 3 mo minimum criterion used in our study was considered adequate to assess the attachment method for real-world application. The method deemed most likely to succeed, based on current literature, was modified, and uniformly applied to all 11 hawksbills. No turtles were trialled as controls for growth without tracker attachment because of potential intra-species variations in natural growth rate and carapace shape and the relatively low number of trial turtles. However, all trackers in this study were successfully attached, and all turtles continued to grow according to their individual calculated trajectory, providing a good indication that the genuine trackers would stay intact for the following dispersal study on release into the wild without influencing turtle welfare.

4.4. Considerations for future studies

The vertical distance between overlapping scutes was not measured in this study. Doing so could have provided further insight into the roles of silicone and neoprene and should therefore be included in future studies. One important difference between the study environment and the natural environment is the lack of complexity in habitat structure in the captive setting of this study. Although turtles did have access to a platform under which they could wedge themselves, this is minimal compared to the possible damage hawksbills can do to trackers when foraging and resting in natural reef or rock-based systems (Storch 2004, Hays & Hawkes 2018). One further consideration regarding the tracker attachment method that was not addressed in this study was the potential drag that could be experienced by turtles tracked in the wild given the size of the finished attached tracker (tracker plus neoprene and adhesives) compared to the size of the turtles. Drag negatively affects turtles by reducing their swimming speed to cope with increased energetic demands (Jones et al. 2011) and, therefore, future studies should test for this. Finally, future studies should consider obtaining an in-water weight of the tracker. Although the epoxy and tracker are heavy, the positively buoyant neoprene may reduce the weight of the attachment in water.

4.5. Conclusion

Publishing replicable tracking data for sea turtles is important and requires optimised protocols. For best data collection and animal welfare results, tracker attachment methods should be tested and adapted for each species and life-stage. The methods developed for neonate green and loggerhead turtles (Seney et al. 2010, Mansfield et al. 2012, 2021), adapted for oceanic-stage Kemp's ridley turtles (Seney & Landry 2011, Putman & Mansfield 2015), and described here for new recruit-sized juvenile hawksbill turtles demonstrate attachment longevity (>3 mo) in a little studied size-class of turtles without notable negative welfare implications (no notable scute damage or disfigurement). As such, this study serves as a valuable tool for researchers and conservation groups aiming to study juvenile hawksbill turtles' dispersal patterns and foraging ground usage. Moreover, the method developed here may be adapted to other aquatic reptiles in future studies.

Acknowledgements. The authors extend many thanks to Kevin Bairos-Novak, Kevin Erickson, Scott Smithers, Clayton Voon, Greg Suosaari, Kevin Lay, Courtney Chilton, Alex Leurquin, Tory Stoddard, Jordan Drake, Kezia Drane, Bethany Adomanis, Emily Webster, and all volunteers at JCU Turtle Health Research for their support and assistance on this study. This study was funded by the James Cook University College of Public Health Medical and Veterinary Sciences.

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Editorial responsibility: Graeme Hays,
Burwood, Victoria, Australia
Reviewed by: 2 anonymous referees

Submitted: December 21, 2021
Accepted: November 23, 2022
Proofs received from author(s): January 13, 2023