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Research Article

Resilience in the Depths: First Example of Fin Regeneration in a Silky Shark (*Carcharhinus falciformis*) following Traumatic Injury

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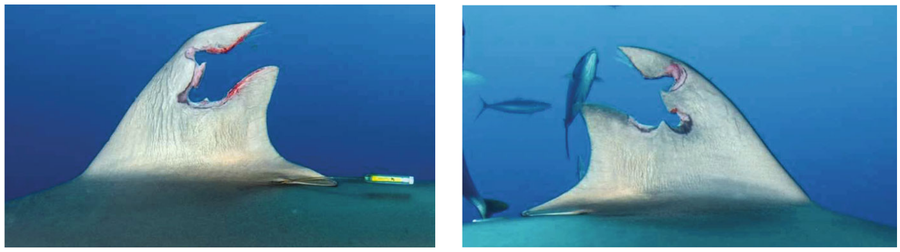
Tissue regeneration and wound healing remain extremely understudied in elasmobranchs as many wounds are recorded through one-off opportunistic observations with an inability for long-term monitoring of individuals. This study demonstrates partial fin regeneration of a silky shark (*Carcharhinus falciformis*) almost one year after a traumatic injury that resulted in a 20.8% loss of the first dorsal fin. The shark was photographed 332 days after the recorded injury with a newly shaped dorsal fin that had healed to 87% of the original size. Photographs provided by divers allowed for accurate measurements of fin growth, confirming an approximate 10.7% increase in fin area, indicative of tissue regeneration. Wound healing rate was calculated to conclude that the initial wound reached complete closure by day 42, which is analogous with other elasmobranch healing rates. Prior to this study, only one other record of dorsal fin regeneration had been documented in a whale shark. This provides the first evidence of dorsal fin regeneration in a silky shark and contributes to the limited studies of wound healing rates in sharks. This newfound insight into tissue regeneration and wound healing underscores the importance of further research to understand how they respond to traumatic injury in the face of mounting environmental challenges, both natural and anthropogenic. Additionally, this study exemplifies the power of collaboration between researchers and the public, including photographers and divers, to expand the scope of research studies and bridge the gap between science and society.

1. Introduction

Elasmobranchs are known to have a high capacity for wound healing, but monitoring and calculating the healing process of wild species are difficult due to the inability to observe individuals over time [1–6]. Sharks have evolved mechanisms to rapidly heal wounds as they are susceptible to them due to both natural and anthropogenic threats in the open ocean. External injuries to sharks are a natural occurrence incurred through mating events, copulation or aggressive behaviors, or attempted predation events [4, 7, 8]. Anthropogenic injuries sustained from marine debris, vessel strikes, research studies, or fishing have become increasingly more common as human and shark space continues to overlap [2, 9–11]. These injuries are more likely to produce long-term physiological adjustments, changes in behavior, and even death, making it important to understand the ability for species to recover [6]. While sharks are considered to have a high propensity for wound healing, studies that document this healing are sparse, and there is limited understanding of the biological mechanisms behind it [1, 12]. Additionally, there is a general lack of samples demonstrating wound healing, as species are negatively buoyant and sink following traumatic and deadly injuries without an opportunity for study [10].

Early studies of wound healing in sharks revealed epidermis regeneration after 3 weeks, reducing the size of the wound up to two-thirds the original size with dermal denticle formation completed after four months [13]. A male sicklefin lemon shark (*Negaprion acutidens*) was documented with a 20 mm vertical laceration to its second dorsal fin that healed over one year until it was almost undistinguishable [14]. Similarly, healing rates over 225 days were recorded in reef manta rays (*Mobula alfredi*) during which



(a) (b)

Figure 1: Photograph of the dorsal fin of a male silky shark (*C. falciformis*) taken during a dive in Jupiter, Florida, on July 31, 2022, by Josh Schellenberg.

they completely recovered from shark bite wounds [15]. Wild juvenile white sharks (*Carcharodon carcharias*) have been recorded to heal major lacerations caused by boat propellers over nine months, and grey nurse sharks (*Carcharias taurus*) have been recorded to heal hook injuries over six months [16, 17]. The rate of healing may be related to external environment, as suggested in teleost wound studies [18]. While wound healing rates have been previously documented, only one example of dorsal fin regeneration exists to date. Womersley et al. [6] documented a whale shark missing the top portion of the first dorsal fin, but time elapsed since the injury was unknown at first sighting. Five years later, the shark was photographed again with a completely healed dorsal fin, regenerating over 6% of fin tissue and regaining the original rounded shape.

This study documents the healing of an adult male silky shark (*Carcharhinus falciformis*) in Jupiter, Florida 332 days after sustaining a traumatic injury to the first dorsal fin. Silky sharks have been known to frequent the warm waters off the coast of Florida during summer months, but their seasonal migration routes remain understudied [19]. As one of the most abundant large sharks in the world, they are also one of the most common bycatch species in high-sea fisheries and are classified as near threatened globally, and vulnerable in the Eastern Central and Southeast Pacific and the Northwest and Western Central Atlantic by the IUCN Red list [19]. The primary threat to silky sharks is fishing pressure, which is very high throughout their known distribution [20]. In some areas of the world, such as the Indian Ocean, silky sharks dominate fishery catch and account for up to 80% of directed shark catch [21]. Silky sharks primarily reside in deep waters with bottom depths down to 4000 m, following continental shelves and adjacent to deepwater reefs [19, 22]. In South Florida, the continental shelf reaches closer to the coastline, creating a unique opportunity for shark diving as it brings many pelagic species in closer to shore. In July 2022, an underwater photographer and diver captured images of a silky shark with unusually shaped cuts throughout the dorsal fin while diving in Jupiter, Florida. This diver was aware of a study the author was previously involved in that included satellite tagging several silky sharks in this area just a few weeks prior and submitted the photos for identification. The cuts through the dorsal fin fit the size of the satellite tag that had been placed on the shark for the previously mentioned tracking study. Due to the precision and pattern of these cuts, it is concluded that the most plausible explanation of the injury resulted from purposeful removal of the satellite tag with a sharp object. Furthermore, the bolts used in the attachment method are less than one centimeter in diameter and would not leave the size hole seen here in this injury if the tag were to fall off naturally. Silky sharks are commonly captured by recreational fishermen in this area during the summer months but are illegal to retain, increasing the likelihood that this shark may have been captured during a fishing trip and the tag opportunistically removed; however, the reason and method for tag removal are not speculated.

The shark was not spotted again in 2022, presumably leaving Jupiter to continue its seasonal migration. In June 2023, a male silky shark with an oddly shaped dorsal fin appeared in Jupiter, Florida, and was photographed by multiple divers. The photos were submitted again to the author, and it was confirmed by tag ID number that this individual was the same shark that had the traumatic fin injury the prior year. This provided a unique opportunity to investigate how the shark recovered from a large wound through photo evidence over a known period and calculate healing rates for the first time in this species.

2. Methods

Multiple silky sharks were tagged with Wildlife Computers SPOT-258 satellite tags in June of 2022 to track migration patterns off the coast of Jupiter, Florida, for a separate study that the author was involved in. On July 31, 2022, a diver photographed an adult male silky shark with large cuts out of the first dorsal fin (Figure 1). It was confirmed by the National Oceanic and Atmospheric Administration (NOAA) dart tag still present under the dorsal fin that the shark was previously satellite tagged as part of said study only a few weeks prior as all sharks were tagged with both NOAA tags and satellite tags (Figure 2). The unique tag number was used to identify the shark and its previously attached satellite tag. The injury occurred between 19 and 32 days prior to being photographed as the original tagging date and last transmission of the satellite tag are known. Satellite tags only send transmissions when above water, so it is likely that after removal, the tag was either dropped into the ocean or damaged. All satellite tags from the previously mentioned study transmitted for a period greater than one year with the exception of this individual.

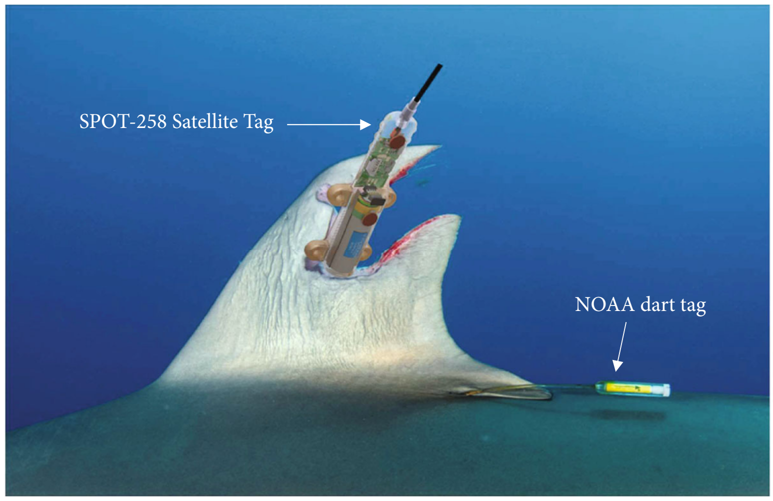


Figure 2: Overlay of SPOT-258 satellite tag with dorsal fin wound of silky shark. Tag rendering from Wildlife Computers, photograph by Josh Schellenberg.

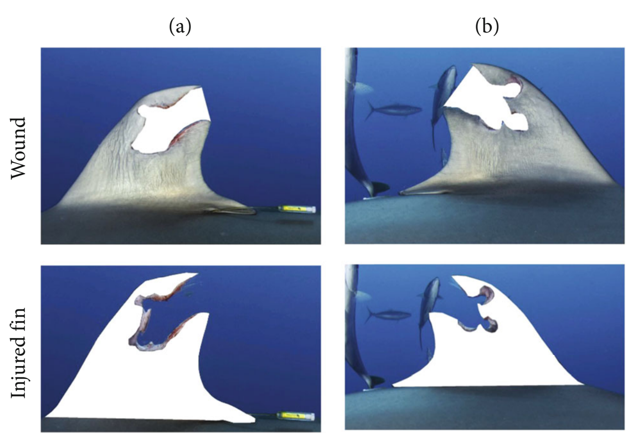


Figure 3: Areas (white) measured in ImageJ to calculate "wound" and "injured fin" (a, b).

2.1. 2022 Wound Calculation. ImageJ software by Schneider et al. [23] was used to calculate an estimated percentage of fin loss using the photos provided by divers. The scale was set using the known length of the NOAA dart tag to provide accurate measurements. Using the freehand and polygon tools, the wound was traced 10 times and averaged to minimize human error. The average of both sides was added together to become the total estimated "wound" size (left 202.6 mm, right 325.5 mm). The remaining fin tissue was measured using the same method to represent the "injured fin" size (Figure 3). To estimate the original size of the dorsal fin before injury, the "wound" and "injured fin" were added together (S1).

2.2. 2023 Healed Fin Calculation. 332 days later, divers spotted the same silky shark again in Jupiter, confirmed by the NOAA dart tag number. The shark did not show any sign of infection or declining health and was observed to be swimming normally (diver's recollection). The dorsal fin looked to have completely healed so that no open wounds remained. In comparison to the previous photos, it appears that the top portion of the fin fused together with the bottom and tissue filled in the middle to form the newly shaped dorsal fin (Figure 4). The dermal denticles that mark the scar of where the wound was appear in a lighter color than the surrounding skin, showing where new fin growth has appeared. The total area of the dorsal fin was measured 10 times and averaged for both the left and right images using the freehand and polygon tools in ImageJ (Table 1).

2.3. Fin Regeneration Calculations. ImageJ was used to measure the left and right sides of the dorsal fin using images provided by divers. Measurements were taken using the freehand and polygon tool and repeated 10 times and averaged, for both sides. An unpaired t-test was used to determine the significant difference between the injured fin and the healed fin for each side (S2).

2.4. Estimated Healing Rates. The rate of growth was calculated using an exponential growth equation:

$$x(t) = x_0 * \left(1 + \left(\frac{r}{100}\right)\right)^t \tag{1}$$

where x_0 is the original value, r is the rate of change per year, and t is the time elapsed. After the rate of growth was determined, the same rate was applied to estimate the wound closure rate (Figure 5).

It is important to note that because the measurements are taken from 2D images, it is not possible to account for total volume of the wound or fin, and thus, all averages are surface areas. This limitation was mitigated by comparing both the left and right sides of the fins separately, as well as comparing all measurements to the original wound sighting to define relative change over time regardless of injury volume. Moreover, it is unknown exactly when the injury occurred, so the wound could have been larger in size than calculated here as most wound healing occurs in early days.

(a)

(b)

Figure 4: Silky shark dorsal fin (a) healed taken May 2023 by John Moore. Silky shark dorsal fin (b) healed taken June 2023 by Josh Schellenberg.

Table 1: Measurements taken in ImageJ used in calculations.

Area measured	Estimated total area of both sides Left and right combined (mm)
Wound	528.1
Injured fin	2005.3
Estimated original fin	2533.4
Healed fin	2220
Fin regeneration	214.7

Additionally, the rate of fin regeneration is an estimate as there are only two measures one year apart, and this rate is more likely to be faster following the initial wound injury and slowed towards the end of the year.

3. Results

The dorsal fin in 2023 showed a 10.7% increase of area compared to the 2022 injured fin (Figure 6 and Table 1). The wound accounted for approximately 20.8% of the estimated original dorsal fin, meaning that nearly half of the fin loss has regenerated over one year. Using the estimated size of the wound and remaining fin from the first sighting, the regrowth was calculated to estimate that the dorsal fin has healed to ~87.6% of its original size. When comparing the injured fins, left and right measurements were compared to the healed fin measurements. Both sides show significant difference from their original values (left $p = <0.0001$, right $p = 0.0002$), further confirming that dorsal fin tissue did regenerate over 332 days. The wound reached 90% closure by day 42 (Figure 5).

4. Discussion

The silky shark was missing an estimated 20.8% of its original dorsal fin when it was seen in 2022. The dorsal fin had increased 10.7% in area by the second sighting, 332 days later. Due to the statistically significant difference between the size of the injured fin and the healed fin, this size difference is attributed to tissue growth and thus evidence of fin regeneration. While the healing rate and regenerative capabilities of sharks are severely understudied, based on the rate of growth over one year, this shark has the potential to recover completely in 2024 after traumatic injury (Figure 5). The healing rate recorded in this silky is comparable to previously recorded rates and supports the growing evidence that elasmobranchs have an exceptional ability to recover from traumatic injuries. The wound closure of the silky shark in this study is analogous with other elasmobranch wound healing rates, where wound closure can occur within one month and the injured area returning to normal within one year (Table 2). With 90% wound closure suggested at day 42, this rate is like that found in whale sharks (35 days). For sharks, slow healing rates in the previously mentioned studies on grey nurse sharks and juvenile white sharks were attributed to cold-water environments [8, 16, 17]. The faster healing process of whale sharks (*Rhincodon typus*) recorded by Womersley et al. [6] is attributed to their use of shallow and warm environments, aiding in the healing process. However, little is still known about the extent to which these variables contribute to wound healing rates due to lack of observations, but the quick healing of the silky shark presented here may be attributed to it spending more time in warm waters.

Even less is known about the tissue regeneration of an amputated appendage in elasmobranchs, and there exists only one other record of dorsal fin regeneration in sharks [6]. Of the few studies to investigate tissue regeneration in sharks, it is concluded that the skeletal muscle in sharks has regenerative capability, potentially due to high concentrations of omega-3 polyunsaturated fatty acids [5, 25, 26]. However, there are no studies identifying the mechanisms behind dorsal fin regeneration or the internal composition of the healed fin and should be a topic for future studies.

Sharks possess evolutionary mechanisms to deal with traumatic injuries that include a combination of molecular adaptions for wound healing, immediate anti-inflammatory responses, and a unique skin microbiome working in tandem with protective dermal denticles [1, 3, 25, 27]. The successful healing of this male silky shark following the forceful removal of a satellite tag demonstrates the regenerative capabilities of fin tissue in this species. Information on the wound healing process of sharks can have broad management applications, such as the development of proper animal handling techniques, assessing human-related threats, as well as implications for researchers who use satellite telemetry methods [1, 6]. A study by Heim et al. [28] demonstrates the complete fin injury closure in great hammerhead sharks (*Sphyrna mokarran*) following the loss of

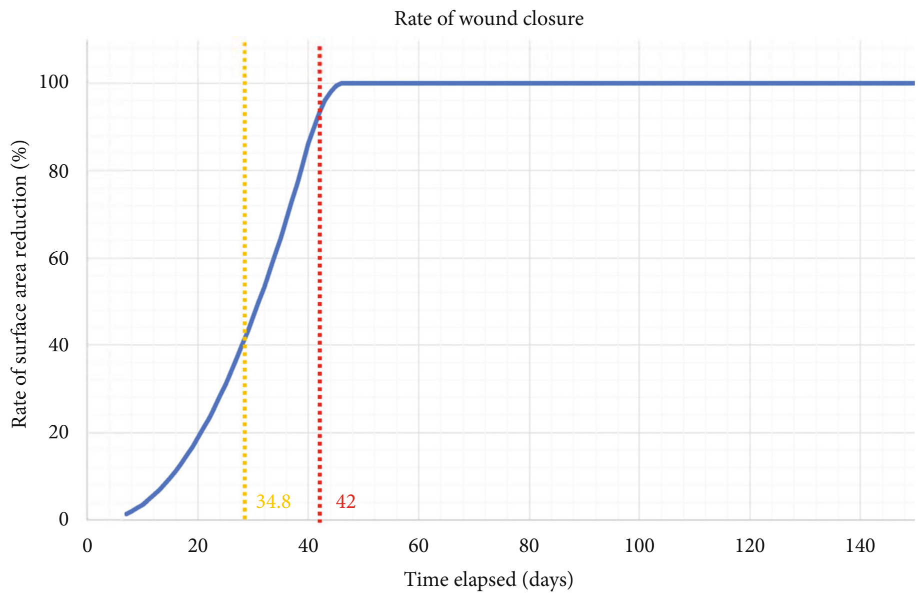


Figure 5: Temporal evolution (days since initial wound sighting) of wound healing showing total surface area (mm). Best fit exponential model (blue line) where x intercept equals 42 days when 90% healing is reached (dotted red line). Wound closure rate for whale sharks [6] is compared in yellow.

(a) (b)

Figure 6: Overlay of 2022 and 2023 dorsal fin photos showing regrowth.

geolocating tags, demonstrating their ability to completely recover naturally after satellite tag placements. While the injury presented here in this silky shark is not due to wounds caused by the satellite tag itself, it does provide anecdotal evidence that silky sharks are capable of healing from the small holes where satellite tags attach to the dorsal fin and their recovery after tags naturally migrate out of the fin over time.

While the incident of injury remains disheartening, the outcome has provided an extraordinary opportunity to investigate the healing and regenerative abilities of silky sharks following both natural and human-induced injury. Furthermore, these findings have implications for the other silky sharks tagged in the same study. As their satellite tags eventually dislodge from their fins, it is now demonstrated that they possess the potential to heal from wounds left behind from the tags. Improving our comprehension of their healing mechanisms may inform better conservation and tagging practices. Normally, satellite tags fall off or migrate out of shark fins over time naturally, leaving behind little to no evidence that there was ever a tag [28], author's observations]. In this case, the silky shark was able to not only heal this large wound but also regenerate fin tissue to almost 90% of its original estimated dorsal fin size.

This study also serves as an example of how underwater photographers and the public can work with scientists to advance research. This situation highlights the need to further educate the public about satellite tagging studies, to potentially avoid citizen interference with research due to lack of understanding, as well as elicit the help of divers and photographers to monitor healing from tagging studies. While scientific research and data collection are integral to conservation, the success of such studies hinges on fostering strong ties with local communities. Engaging the public in research studies can help bridge the gap between community awareness and scientific research, providing more eyes to monitor changes that scientists would otherwise miss [29]. Without photo documentation of this silky shark's injuries, it would be impossible to study wound healing or fin regeneration for this shark. Because silky sharks display highly migratory behavior, it is likely that this same individual will return to Jupiter, Florida, in the

Table 2: Wound healing rates of previous elasmobranch studies.

Species	Wound type	Healing rate	Study
Blacktip reef shark (*Carcharhinus melanopterus*)	Laceration from vessel collision	27 days	Chin et al. [1]
Pelagic stingray (*Pteroplatytrygon violacea*)	Circle hook expulsion	28 days	Francois et al. [24]
Whale shark (*Rhincodon typus*)	Vessel collision	35 days	Womersley et al. [6]
Blacktip reef shark (*Carcharhinus melanopterus*)	Bite wound	40 days	Chin et al. [1]
Sicklefin lemon shark (*Negaprion acutidens*)	Dorsal fin laceration	60 days	Buray et al. [14]
Nurse shark (Ginglymostoma cirratum) and leopard shark (Triakis semifasciata)	Dermal denticle removal	4 months	Reif [13]
Reef manta ray (*Mobula alfredi*)	Vessel strike	126-295 days	Marshall and Bennett [15]
Grey nurse shark (*Carcharias taurus*)	Hook injury	6 months	Bansemer and Bennett [17]
White shark (*Carcharodon carcharias*)	Major laceration from boat	9 months	Towner et al. [16]

summer of 2024. Should this shark be photographed again, future analysis will be run to track healing progress and estimate if there is continued fin regeneration to provide even more accurate data on fin regeneration rates in this wild species.

5. Conclusion

This is the first documented evidence of fin regeneration in silky sharks and provides an estimated wound healing rate comparable to other elasmobranchs. Prior to this study, there existed only one other documented case of dorsal fin regeneration [6] making this study only the second record of dorsal fin regeneration in sharks to the author's knowledge. While fin regeneration was observed in this silky shark, it cannot be concluded if this ability is applicable to all individuals of this species, and it may also be dependent on environmental factors such as temperature. Like other cases documented by Womersley et al. [6], there was enough remaining fin to fuse together, and this may serve as a base for continued growth that would be missing in a full amputation of the fin. Previous studies have found that cartilaginous rays that are severed within pectoral fins have no ability to regrow due to the lack of blood supply to the fins [30]; therefore, it is possible that the fin regrowth of this silky shark lacks the cartilaginous fin rays and is comprised only of scar tissue and dermal denticles. Records of appendage amputation should be documented and recorded where possible to further our very limited understanding of this phenomenon and in the matter of which it regrows.

In conclusion, the traumatic injury led to the first recorded instance of fin regeneration in silky sharks and offered an unprecedented opportunity to study this phenomenon. As a highly mobile species, silky sharks in the Northwest Atlantic are vulnerable to human-induced threats such as bycatch in commercial fishing operations. In the Northwest Atlantic, overfishing has contributed to the rapid decline of coastal shark species to a magnitude that suggests that several species are at risk of extirpation [31]. Silky sharks are capable of migrations that cover distances of over 3,500 kilometers [32], yet movement and migration patterns of silky sharks in the Northwest Atlantic are not well documented. The data collected by the satellite tag placed on this individual would have contributed to the limited research on habitat use and migration corridors for this area. Not only did the forceful removal of this satellite tag cause traumatic injury to the shark, but it negatively impacts the entire species through loss of invaluable data needed for increased protection. Telemetry data have been used to effect policy change from scales of only a few kilometers up to open oceans, influenced Marine Protected Area designs, contributed to stock management, and helped change the conservation status of marine species [33–37]. While this injury provided the first record of fin regeneration in silky sharks, the data collected by the satellite tag could have provided data to better protect and conserve an entire species. Beyond scientific revelations, this study highlights the pressing need for effective communication between researchers and the local communities, amplifying the impact of marine conservation.

Data Availability

Measurements captured in ImageJ to determine the size of wound and fin tissue at initial injury and after are available in the Supplementary Material file. Original photographs are available upon request.

Conflicts of Interest

The author declares no conflict of interest.

Acknowledgments

These findings would not have been possible without the documentation of underwater photographers Josh Schellenberg and John Moore who are thanked for their support of shark research and advancement of science. It is through relationships built between researchers and the public that have the potential to create the most change. The initial tagging study (ongoing) that the author was involved in was funded by the University of Miami Shark Research and Conservation Program in 2022.

Supplementary Materials

Files include fin measurements taken in ImageJ and results of the t-test. *(Supplementary Materials)*

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