Journal of Marine Biology & Oceanography

Research Article

A SCITECHNOL JOURNAL

Characterization of Blacktip Shark Feeding Apparatus Injuries Due to Hook Ripping

Erich K Ritter[1,2]*

Abstract

During sport fishing for bottom-dwelling fish, non-targeted sharks occasionally take a bait, requiring hook removal from the shark before release. It is an occasional practice to rip hooks out of the shark's mouth instead of bringing the shark to the surface and properly removing the hook. "Hook ripping" can severely injure the feeding apparatus of the shark, especially along the lower jaw and joint area. In severe cases, it may eliminate a shark's ability to feed, leading to the death of the shark. At one site in South Africa, at least 30% of the population of blacktip sharks, *Carcharhinus lismbatus*, were observed to have injuries to their mouths consistent with hook ripping, indicating that this practice is a considerable concern for the survival of resident sharks in this area. The severities of the wounds were evaluated from the perspective of remaining feeding capabilities, and suggestions made on how to reduce the damage of hook ripping.

Keywords

Blacktip shark; Injury; Broken jaw; J-hooks; Hook ripping

Introduction

Recreational fishing restrictions on permitted species and bag limits vary among countries, but the well-being of non-targeted animals that are released in the process is generally not a primary concern of the governing agencies. This is also true for recreational bottom fishing and trolling along the South African coast [1-3]. Although teleosts are the target group during recreational fishing, the possibility of a shark taking the bait or lure cannot be avoided due to the use of non-selective fishing gear [3-5]. Since sharks are generally not sought after during sport fishing, and are not allowed to be sold, fishers sometimes try to rip the hook, further called "hook ripping," out of the shark's mouth once they realize what they have on their lines, instead of bringing the animal alongside the boat and removing the hook properly. Depending on leader material and strength, as well as the type of hook and its position in the shark's mouth, hook ripping can injure the shark, especially along its lower jaws (Figure 1). In addition to lower jaw damage, hook ripping can also affect jaw articulation and damage the supporting ligaments. Depending on the severity of the injuries, the injuries can temporarily and permanently impact the feeding mechanics of a shark.

The lower jaw of a shark, termed the mandible or Meckel's Cartilage (MC), is an essential part of suction feeding [6,7], where during the expansive phase it is quickly depressed while the buccopharyngeal cavity and branchial apparatus concurrently expand. Through this mechanism, the pressure of the buccopharyngeal chamber is decreased, which enables the prey or food in front of the shark's snout to be siphoned into the chamber [8]. If the shark is no longer able to create the needed suction pressure, it must compensate by shifting to smaller food pieces. This diet shift leads to a set of problems for the newly impaired shark.

Figure 1: The injured lower jaw of a blacktip shark caused by hook ripping.

Moreover, it is not just suction feeding that can be affected by injuries sustained through hook ripping. Gouging, the other major feeding mechanism that involves the cutting of flesh out of a food source that is larger than a shark's bite volume, can also be negatively impacted. This form of feeding requires the MC's teeth to first get a firm grip on the targeted prey before the upper teeth can start cutting through the flesh. Commonly, the lower teeth must be erected before being able to penetrate the prey's surface [9]. This teeth positioning is facilitated through a flexible and elastic tooth attachment with the underlying connective tissue sheet, the dental ligament. By pulling the sheet, the teeth are erected accordingly. Hook ripping may impair or completely destroy this mechanism, thus the teeth positioning for holding the prey could then fail and make successful gouging impossible.

Jaw injuries among sharks due to fishing hooks are a common problem [10-13]. Over a duration of nine days in April 2018, 12 blacktip sharks, *Carcharhinus limbatus*, were videotaped that carried such hook-related wounds in Protea Banks, South Africa. Protea Banks, an area that will be declared an MPA (Marine Protected Area) in August 2019 [14], is a dune reef lying about 8 km off the Kwazulu-Natal coast with a depth of about 25-60 m. Protea Banks is approximately 3 km long with a series of caves, gullies, and some small formations, and home to 9 elasmobranch species and over 40 teleost species [15].

During each dive, six to nine sharks were present, of which three to four of them showed jaw injuries. Since the sharks with jaw injuries could easily be recognized, and so acted as marked sharks, the calculated size of the population ranged between 18 and 40 individual sharks. The aim was to quantify the severity of the injuries

***Corresponding author:** Erich K Ritter, Shark Research Institute, Princeton, NJ 08542, USA, Tel: 7863013310; E-mail: eritter@uwf.edu

Received: May 06, 2019 **Accepted:** June 14, 2019 **Published:** June 24, 2019

to the shark feeding mechanisms and estimate the fitness and survival consequences of those injuries. Additionally, the type of fishing gear that is commonly used in that area was also examined and changes in fishing procedures are proposed to eliminate, or at least reduce, the number of hook-wounded sharks in the future.

Besides the rather obvious impacts this type of fishing can have on the local blacktip shark population, the long term effect to the local fauna must also be considered. Although blacktip sharks around Protea Banks will soon receive more protection due to the establishment of the MPA, the problem will remain outside the MPA boundaries.

Materials and Methods

Observations of blacktip sharks

Throughout the observation period, all present sharks were estimated to be around 1.5 m long based on length comparison with close-by divers. Blacktip sharks can grow to about 2.5 m [16] but normally do not exceed 2.0 m [17-19].

Several descriptive wound criteria were recorded and grouped into three categories. First, all deformations of the MC were tallied that occurred due to a misalignment of the dual joint articulation [20], consisting of the medial and lateral quadratomandibular joint (QJM, QJL; Figure 2) or a possible broken jaw with intact articulation. Once an MC is mispositioned, a permanent gape with the upper jaw, the palatoquadrate (PQ), is formed (Figure 1). The injuries entailed either the entire MC or parts thereof (Figure 3a). In a fully functional joint area, PQ and MC do not leave any space at the articulation, which is further called the "joint." The second category consisted of sharks that showed injuries to the MC but were still able to control water intake once the MC was lifted to close the natural gape which largely depends on the mandibulohyoid connective tissue sheath (MCTS) inside the MC (Figure 3b). Finally, it was noted how much of the MCTS was passively pulled back from the lower teeth due to the misaligned and/or outward turned MC, and so how many rows of teeth were visible (Figure 3c). In a relaxed position, an uninjured blacktip shark only has its first row of lower teeth visible, all other rows remain covered by the MCTS. In this position, the mouth forms a natural gape to guarantee enough water flow over the gills during natural locomotion.

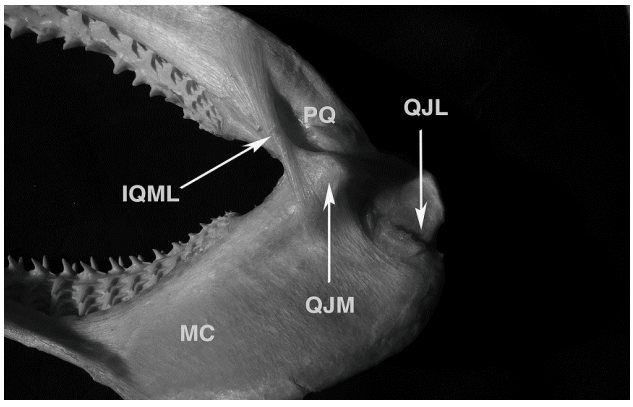

Figure 2: Medial view of the lower and upper jaw. IQML=Inner quadratomandibular ligament, MC=Meckel's cartilage; PQ=Palatoquadrate, QJL=Lateral quadratomandibular joint, QJM=medial quadratomandibular joint.

None of the injured sharks were captured and dissected to conclusively determine the severity of the actual wounds; hence, some of the discussed issues may remain speculative. Nevertheless, it was assumed that an injured MC may lead to decreased fitness and, in severe cases, starvation of the shark due to difficulty capturing and consuming prey.

Fishing practice and gear

Personal interviews were conducted to deduce and detail how sharks sustain injuries when caught during rod and reel sport fishing. Because sharks are not a sought-after group in the region, fishers commonly do not want to make the effort to reel them in and remove the hook properly when they catch sharks during sport fishing. The overall consensus among sport fishers is that reeling in a shark is too exhausting; thus, the alternative is to try ripping the hook out of the shark's mouth once the fishers feel the pull. Fishers trawling for bottom fish around the study site commonly used size 4/0 or 5/0 regular J-hooks with a 90º round bend single barb or triple hooks called Rapalas (Figure 3d).

Results and Discussion

Of the 12 injured sharks, all had injured joint areas and four still had hooks attached to their jaws (Figures 3c and 3d). Six sharks had injuries to their MCs, with some injuries so severe that they could no longer close the natural gape between MC and PQ. Some of the MCs were dislocated and rotated outward. This misplacement led to lower teeth exposure for five of the 12 videotaped sharks. Each of those sharks had at least two rows exposed (Figure 1, Figure 3a and Figure 3c), either on one or both halves of the MC.

An injury to any element of the feeding apparatus of a shark affects its functionality and thus likely impairs suction and gouging, the two most prominent feeding mechanisms among sharks. Suction feeding could be impaired due to an inability to depress or lift the MC, which is largely responsible for initiating the needed suction pressure (Figure 3e). Gouging could be impaired if the MC's teeth along an outward turned jaw are no longer properly erected, and therefore be unable to optimally puncture the prey.

Sharks' teeth fall out regularly and are subsequently replaced [21-23]. As long as hook ripping does not affect supporting nerves, tooth replacement should remain functional. Since all teeth were still present without any discoloration among the injured blacktip sharks, this suggests that either the injuries were still fresh or that tooth replacement was still functional. In the weeks that followed, the initially videotaped blacktips became less frequent until none of them was seen anymore, therefore the functionality of those tooth rows could not be verified. Although newly injured sharks kept showing up after the end of the study period, a clear determination could not be made (R. Mauz, personal communication). Because similarly injured sharks have been described in other regions beyond South Africa [24], post-release mortality cannot be assumed [5] but remains a possibility due to the possible impairment of suction feeding or gouging (Figure 3e).

Damage inflicted to the feeding apparatus

The stability of the PQ and the MC is established through an array of ligaments and tendons with their associated muscles, as well as the hyomandibula and ceratohyale [20]. Blacktip sharks possess the typical hyostyle jaw mechanism of modern elasmobranchs with QJL and QLM forming a dual articulation (Figure 2). This joint orientation resists lateral movement [20]; therefore hook ripping with a force

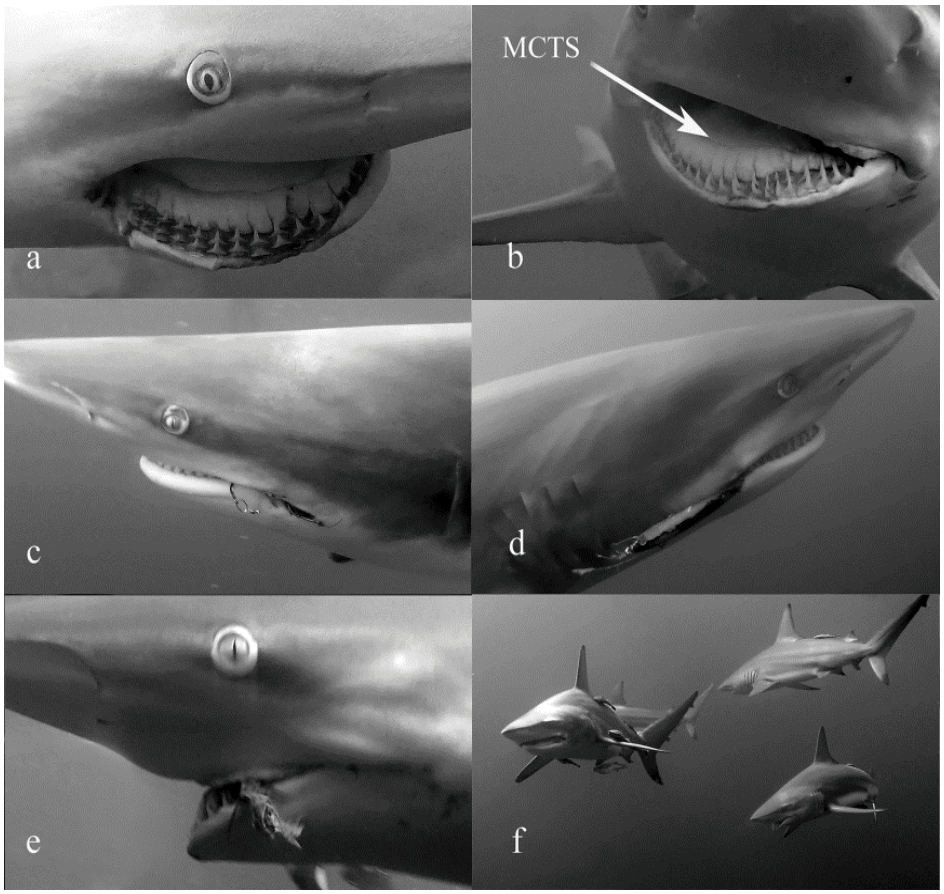

Figure 3: Different forms of injuries to the lower jaw and joint. (a) dislocated lower jaw with permanent exposure of lower tooth rows, (b) MCTS (=Mandibulohyoid connective tissue sheath), (c) typical mouth corner position of a Rappala triple hook, (d) implanted J-hook, (e) food stuck between jaws due to reduced suction ability and (f) during each dive more than one shark showed injuries to its jaws.

perpendicular to the ligaments' support system of the joint could cause a dislocation [4], leaving a clear gap between the two jaws in the corner of the mouth (Figure 1). One of the main ligaments affected is the inner quadratomandibular ligament (IQML). Depending on the force with which a hook is pulled, other ligaments in addition to the IQML could get torn or ripped from their entheses as well [20]. Losing the stability of those ligaments could be the reason why the MCs of the more severe injuries looked as if they were rotated outward. This effect could be intensified by a still intact ventral coracomandibularis muscle [25].

The impacts of hook ripping may be partially mediated by the structure of the MC, which consists of two halves connected along the symphysis through connective tissue. The symphyseal tissue belongs to the palatoquadrate-mandibular connective tissue sheath that forms the primary teeth attachment along the upper and lower jaw. The symphyseal tissue may allow some torque and stretch while hook ripping occurs, and thus may have the ability to realign the two halves again to some extent once the pull on the hook ceases.

If hook ripping occurs, chances are that the PQ, in addition to the MC, is pulled from its resting position, causing further damage. Although this may be the case on occasion, permanent injuries to the PQ may happen less frequently due to the fact that this jaw can naturally be protruded forward and outward during gouging, thus giving the PQ and its attachment to the brain capsule some additional flexibility. That no injuries to the PQs among the injured blacktips were observed is somewhat remarkable, considering how a shark tends to suck in food even if it is hanging on a suspended hook. Most likely, PQ injuries were not seen because the sport fishing boats in the areas were trolling, with baited hooks pulled behind the boats. This mode of fishing could reorient the point of a hook to the extent that MCs are then more likely to be punctured.

In a previous study, juvenile lemon sharks, *Negaprion brevirostris*, were exposed to experimental rod and reel activities in an effort to characterize subsequent injuries caused by hooks [26]. In that study, not only were the MCs damaged by the hooks, but also the basihyal cartilage that is closely connected to the MC. Although no such injuries were visible in this study, this type of injury may have been present in the observed blacktip sharks, though not verified through gross anatomy.

Despite the visual damage to the jaws and joint area of the observed blacktip sharks, there is also the possibility that some of the hooks were swallowed before ripping, as demonstrated in previous studies [27]. As such, a stomach- or "gut"-hooked shark may also have potential injuries to the oesophagus and liver due to gastric perforation [28].

Such damage to inner organs could cause peritonitis, gastritis, and other problems [10,28]. These types of injuries would then increase the overall mortality rate of hook-ripped sharks. It has been estimated [5], albeit from long lining studies, that stomach-hooked sharks may have a mortality rate as high as 50%, but the general understanding of post-release survival of hooked sharks is that such mortality could be lower than this estimate [29].

Different trauma caused due to hook ripping

Hooked sharks experience severe physiological and psychological trauma, even without hook ripping. A captured shark mostly thrashes around and launches quick bursts of speed to free itself [30]. The duration of these speed bursts is mostly no longer than a few seconds at one time, interrupted by either resting on the suspended line and being pulled along or, if the site is shallow enough [31-33], resting on the bottom should the hook belong to a stationary setup. Once on a hook, different forms of trauma are manifested, although some of the effects may not appear until after release [26,34,35]. Together with the purely anatomical injuries, these effects also add to the collective impacts of physiological stress [31,36,37]. Such stress can manifest itself through ionic, metabolic, or haematological changes [12,38,39] such as an increase in lactate, which is largely produced during speed bursts [40,41]. Related experimental capture and release data that included blacktips highlighted their particular sensitivity to such procedures [42,43].

Since the injured blacktips in this study had roughly the same length, the passive body weight resistance against hook ripping may have been constant among observed sharks. However, it cannot be concluded that all the sharks fought in the same way once on the line, thus leading to variable stress levels and severity of injuries.

Where to go from here?

During the nine-day observation period at Protea Banks, a calculated minimum of 30% of the blacktip sharks carried injuries to their feeding apparatus (Figure 3f), demonstrating that the practice of hook ripping is frequent enough to warrant addressing in order to identify what steps, legal and otherwise, locally and nationally, should be taken to avoid or at least reduce these types of injuries. Without changing fishing practice regulations to avoid accidental shark hooking, injured and dislocated jaws among sharks will remain a problem in Protea Banks, South Africa, and elsewhere. Although this project focused on blacktip sharks in a single area, concern about hook ripping is not limited to this species and efforts to curb the practice should be extended to all the other shark species detected in local fishing surveys [1,3,44].

Although the law does not specifically prohibit the practice of hook ripping in South Africa, a similar fishing technique specified as "jerking of a hook" is designated as against the law in the South Africa's Fishing Regulations and Fishing Permits guide. Thus, the prohibition of jerking of a hook could easily be extended when hooking undesired sharks.

However, even without changing the law, fishers could contribute to preventing such damage. The most forward way would be for conservationists to appeal to their ethos and pride to release the shark with the least damage possible. Since 2011, a verbal agreement exists for an 18.1 km² area around Shelly Beach that specified no bait/reef fishing or chumming the water between August 1 and November 30 [15]. Although this agreement has no legal binding, and just follows the local guidelines of the Shelly Beach Ski Boat Club [15], it shows that common ground exists between different interest groups. As part of such guidelines, proper shark removal from hooks could be outlined.

Due to the stronger pull of a shark compared to bottom-dwelling fish, it is easy to identify when a shark is on a line. In these cases, the shark should be brought to the surface, alongside the boat, to either remove the hook or at least cut the leader as close to the hook as possible. If a tail rope is used to secure the shark further, special attention should be given to skin burns due to potential thrashing [45] so as to not exacerbate the already ongoing physiological and psychological trauma. Furthermore, handling time should be kept to an absolute minimum since non-bottom dwelling sharks must keep moving to guarantee water flow over their gills. In fact, even short periods of forced standstill can negatively impact the likelihood of survival, not only because the already-mentioned effects could intensify, but also because damage to gills, for example, could occur once exposed to air [46].

Based on South Africa's national action for the conservation and management of sharks, South Africa hosts an estimated 850,000 shore and estuarine fishers, including jet ski fishers, and over 30,000 recreational and close to 6,000 charter yearly boat launches along the Kwazulu-Natal coast [47,48]. These numbers indicate that the potential impact of non-regulated fishing procedures for sharks could be tremendous.

It may seem easy to adopt procedures to help release a shark as quickly as possible, with the goal of minimizing damage to the shark. However, angry fishers have been observed to stab sharks to death when having them alongside the boat (R. Mauz, personal communication), indicating that a simple gentleman's agreement against hook ripping is unlikely to be successful along the South African coast. Furthermore, it has been estimated that fishers lose anywhere from 50% to 80% of their catch due to depredation [15], which makes these outbursts understandable. The decision to kill a shark seems even more likely should a fisher lose a highly prized yellowfin tuna (*Thunnus albacares*) to a shark, and then have a shark on the line soon after. However, such a negative attitude towards sharks may only represent a small proportion of fishers in the study area [49].

Appealing to the ethics held by a sport fisher may or may not be successful; thus, existing fishing gear must be legally altered to minimize the injuries to hooked sharks. First, when trolling for fish, fishers should reduce the hook size to reduce the likelihood of catching a shark [50]. In addition, hook swallowing could be minimized by replacing the commonly used J-hooks with circle-hooks [51-53]. These hooks are aligned perpendicularly to the hook's shank, thus reducing the possibility of intestinal wounds [54-56]. In addition, all hooks should be non-plated for quicker dissolving. Fishers should also consider the actual position and orientation of the hook– pointing up or down– when being bitten into by the shark. Depending on a boat's speed, the length of the line, and the size of bait attached, hooks may shift into a somewhat horizontal position when being pulled behind a boat, thus changing the angle of penetration into the jaws [57]. To what extent the actual boat speed adds to injuries is unknown and therefore needs to be investigated.

A bleak future for sharks

Shark populations around the world are declining [58,59] with estimates of 70 million [60] to 100 million animals [59] harvested

annually. Because sharks are the most abundant top and super predators over 50 kg on our planet, they are invaluable for the stability of marine ecosystems [61-64]. A further decline will lead to irreversible damage, not just to shark population densities and species compositions [65], but to the entire marine ecosystem, as well. Although both governmental and non-governmental agencies have taken a stand against commercial shark overfishing, regulations and laws are still too few and weak to stop this ecological time bomb; therefore, a more drastic approach must be taken. In addition to the above-mentioned changes in fishing gear, binding procedures must be outlined for how to bring caught sharks alongside the boat in order to retrieve a hook. Since it is not just blacktip sharks that would benefit from such changes to the existing law, species-specific guidelines should also be considered [66], including fishery-specific examinations of how individual shark species react to capture stress [43]. It would also be prudent to highlight differences regarding the sex and life stage of the sharks [39].

Together with all the changes and considerations proposed above, the value of sport fishing must be reconsidered, especially for areas outside of MPAs. Because such a large proportion of sharks are estimated to sustain injuries due to sport fishing, it should be examined if recreational catching of fish should even be tolerated and that would involve the inadvertent catching of sharks. Considering the monetary value of recreational fishing in South Africa [2,3,67,68], it seems unlikely that a ban on this type of fishing will be put forth. Thus, the establishment of more no-take marine sanctuary zones than those already in place should be considered. This would give individual sharks a slightly better chance of reaching adulthood and breeding, thus serving to stabilize the population

Unwanted by-catch is a rather complex issue [49,69,70], and even more so where commercial fishing is concerned. These practices often occur in international waters where legal aspects are not easily implemented. Nevertheless, regulatory limits, bans, and change of gear apply to all forms of fishing, independently of nationality, and should be put in place whenever and wherever possible. These changes to fishing regulations must be backed up with appropriately designed field experiments to guarantee the best adaptations to existing fishing laws [30,71], and then monitored through independent observer programs. In addition, management plans outside the boundaries of MPAs must be developed by ecologists and not fishery consultants, otherwise, the survival of some of those hard to protect shark populations will likely not happen [72,73].

Once sharks are gone from a region, socio-economic impacts likely follow

Because sharks depend on an intact feeding apparatus to catch prey, damage to this system will surely negatively impact the fitness of the shark. Considering that at least 30% of the resident blacktips around Protea Banks were observed to be injured, the effects on the local fauna could be devastating should none of these sharks survive, leaving holes within the food web in this area. Protea Banks, as well as other reef systems along South Africa's coast, contain a seasonal mixture of different shark species, with the year-round blacktips, a pelagic species, being also the most mentioned species when it comes to depredations along that coast [74]. Although the situation along Protea Banks, because of its newly established MPA [14], should now improve for these sharks, other areas along the coast keep having this problem, all depending on the percentage of affected sharks, as well as the severity of their injuries.

Despite the size of Protea Banks, the calculated number of blacktip sharks was small. A decrease in shark population density, due to the die-off of some of the affected sharks, could have irreversible consequences, including small-scale extirpation. The calculated population size for Protea Banks ranged from 18 to 40 blacktip sharks, and the possible elimination of 12 injured sharks would have drastic effects on the health of the ecosystem. Even more so since, at least for Protea Banks, no other pelagic shark species have been encountered throughout the data collection, and even after, individuals of other species remained rare throughout the remainder of the year (daily dive log of R. Mauz accessed in January 2019).

In addition to ecological impacts, local ecotourism-related activities, e.g., shark diving around Protea Banks, could feel a negative financial impact, too, should the shark species diversity be reduced [15,75]. Dive oriented ecotourism is big business in South Africa, and any degradation of the local dive sites could irreversibly affect this part of tourism. A reduction in dive tourism would not just affect those operators but also impact hospitality businesses that cater to this activity [76]. Despite declaring Protea Bank an MPA, fishing efforts outside this region will likely still impact this now protected area [77], thus any fishing practice, including hook ripping, should be prohibited within and beyond South Africa.

Conclusion

Fishers should be proud to remove and release undesired shark catches from their hooks unharmed, and so support shark conservation. Because overfishing of sharks is continually increasing and has reached alarming quantities, every contribution to saving the life even of one single shark needs to be pursued, and this approach should also apply to undesirable fishing practices such as hook ripping. If this practice cannot be eliminated, then governmental agencies must at least ensure that hook-related injuries to the feeding apparatus of sharks, as well as to the internal organs, are minimized.

Acknowledgments

Special thanks go to Roland and Beulah Mauz from "Africa Dive Adventures" and to "ProWin" for financially supporting this project.

References

1. Smale MJ, Buxton CD (1985) Aspects of the recreational ski-boat fishery off the Eastern Cape, South Africa. S Afr J Mar Sci 3: 131-144.
2. Brouwer SL, Buxton CD (2002) Catch and effort of the shore and skiboat linefisheries along the South African Eastern Cape coast. S Afr J Mar Sci 24: 341-354.
3. Everett BI, Fennessy ST (2007) Assessment of recreational boat-angling in a large estuarine embayment in KwaZulu-Natal, South Africa. Afr J Mar Sci 29: 411-422.
4. Basemer CS, Bennett MB (2010) Retained fishing gear and associated injuries in the east Australian grey nurse sharks (*Carcharias taurus*): implications for population recovery. Mar Freshw Res 61: 97-103.
5. Campana SE, Warren J, Fowler M, Showel M (2015) Discards, hooking, and post-release mortality of porbeagle (*Lamna nasus*), shortfin mako (*Isurus oxyrinchus*), and blue shark (*Prionace glauca*) in the Canadian pelagic longline fishery. ICES J Mar Sci 73: 520-528.
6. Tanaka SK (1973) Suction feeding by the nurse shark. Copeia 1973: 606-608.
7. Motta PJ, Wilga CD (1999) Anatomy of the feeding apparatus of the nurse shark, *Ginglymostoma cirratum*. J Morphol 241: 33-60.
8. Motta PJ, Hueter RE, Tricas TC, Summers AP, Huber DR, et al. (2008) Functional morphology of the feeding apparatus, feeding constraints, and suction performance in the nurse shark *Ginglymostoma cirratum*. J Morphol 269: 1041-1055.

9. Ramsay JB, Wilga CD (2007) Morphology and mechanics of the teeth and jaws of white-spotted bamboo sharks (*Chiloscyllium plagiosum*). J Morphol 268: 664-682.
10. Borucinska J, Martin J, Skomal G (2001) Peritonitis and pericarditis associated with gastric perforation by a retained fishing hook in a blue shark. J Aquat Anim Health 13: 347-354.
11. Gurshin CWD, Szedlmayer ST (2004) Short-term survival and movements of Atlantic sharpnose sharks captured by hook-and-line in the north-east Gulf of Mexico. J Fish Biol 65: 973-986.
12. Hight BV, Holts D, Graham JB, Kennedy BP, Taylor V, et al. (2007) Plasma catecholamine levels as indicators of the post-release survivorship of juvenile pelagic sharks caught on experimental drift longlines in the Southern California Bight. Mar Freshw Res 58: 145-151.
13. Skomal GB (2007) Evaluating the physiological and physical consequences of capture on post-release survivorship in large pelagic fishes. Fish Manage Ecol 14: 81-89.
14. Department of Environmental Affairs (2019) Notice declaring the Protea Banks marine protected area in terms of section 22A of the National Environmental Management: Protected Areas Act, 2003 (Act No. 57 of 2003). Gov Gaz 42478: 60-63.
15. Labinjoh L (2014) Rates of shark depredation of line-caught fish on the Protea Banks, KwaZulu-Natal. University of Cape Town, 86 pp.
16. Garrick JAF (1982) Sharks of the genus *Carcharhinus*. NOAA Tech. Rept. NMFS Circular 445. 194 pp.
17. Dudley SFJ, Cliff G (1993) Sharks caught in the protective gill nets off Natal, South Africa. 7. The blacktip shark *Carcharhinus limbatus* (Valenciennes). S Afr J Mar Sci 13: 237-254.
18. Killam KA, Parsons GR (1989) Age and growth of the blacktip shark, *Carcharhinus limbatus*, near Tampa Bay, Florida. Fish Bull 87: 845-857.
19. Castro JI (1996) Biology of the blacktip shark, *Carcharhinus limbatus*, off the southeastern United States. Bull Mar Sci 59: 508-522.
20. Motta PJ, Wilga CD (1995) Anatomy of the feeding apparatus of the lemon shark, *Negaprion brevirostris*. J Morphol 226: 309-329.
21. Luer CA, Blum PC, Gilbert PW (1990) Rate of tooth replacement in the nurse sharks, *Ginglymostoma cirratum*. Copeia 1990: 182-191.
22. Overstrom NA (1991) Estimated tooth replacement in captive sand tiger sharks (*Carcharias taurus*, Rafinesque 1810). Copeia 1991: 525-526.
23. Ritter EK, Dellios A (2018) On the separation mechanism between a shark's tooth and its jaw base, with special emphasis on an observation made from a white shark, *Carcharodon carcharias*. Open J Anim Sci 8: 329.
24. Barash A, Pickholtz R, Nativ H, Malamud S, Scheinin A, et al. (2018) Seasonal arrival and feeding of injured coastal sharks at fish farms in the Eastern Mediterranean. J Black Sea/Med Environ 24: 86-90.
25. Wilga CD, Motta PJ (2000) Durophagy in sharks: feeding mechanics of the hammerhead *Sphyrna tiburo*. J Exp Biol 203: 2781-2796.
26. Danylchuk AJ, Suski CD, Mandelman JW, Murchie KJ, Haak CR, et al. (2014) Hooking injury, physiological status and short-term mortality of juvenile lemon sharks (*Negaprion bevirostris*) following catch-and-release recreational angling. Conserv Physiol 2: 1-10.
27. McPhee DP, Leadbitter D, Skilleter GA (2002) Swallowing the bait: is recreational fishing in Australia ecologically sustainable? Pac Conserv Biol 8: 40-51.
28. Borucinska J, Kohler N, Natanson L, Skomal G (2002) Pathology associated with retaining fishing hooks in blue sharks, *Prionace glauca* (L.), with implications for their conservation. J Fish Dis 25: 515-521.
29. Moyes CD, Fragoso MK, Musyl MK, Brill RW (2006) Predicting postrelease survival in large pelagic fish. Trans Amer Fish Soc 135: 1389-1397.
30. Gallagher A, Staaterman E, Cooke S, Hammerschlag N (2016) Behavioral responses to fisheries capture among sharks caught using experimental fishery gear. Can J Fish Aquat Sci 74: 1-7.
31. Frick LH, Reina RD, Walker TI (2010) Stress related physiological changes and post-release survival of Port Jackson sharks (*Heterodontus portusjacksoni*) and gummy sharks (*Mustelus antarcticus*) following gill-net and longline capture in captivity. J Exp Mar Biol Ecol 385: 29-37.
32. Frick LH, Walker TI, Reina RD (2012) Immediate and delayed effects of gill-net capture on acid-base balance and intramuscular lactate concentration of gummy sharks, *Mustelus antarcticus*. Comp Biochem Physiol A 162: 88-93.
33. Guida L, Walker TI, Reina RD (2016) The adenylate energy charge as a new and useful indicator of capture stress in chondrichthyans. J Comp Physiol B 186: 193-204.
34. Mandelman JW, Farrington M (2007) The estimated short-term discard mortality of a trawled elasmobranch, the spiny dogfish (*Squalus acanthias*). Fish Res 83: 238-245.
35. Heberer C, Aalbers SA, Bernal D, Kohin S, DiFiore B, Sepulveda CA (2010) Insights into catch-and-release survivorship and stress-induced blood biochemistry of common thresher sharks (*Alopias vulpinus*) captured in the southern California recreational fishery. Fish Res 106: 495-500.
36. Cliff G, Thurman GD (1984) Pathological effects and physiological effects of stress during capture and transport in the juvenile dusky shark, *Carcharhinus obscurus*. J Comp Physiol A 78: 167-173.
37. Manire C, Hueter R, Hull E, Spieler R (2001) Serological changes associated with gill-net capture and restraint in three species of sharks. Trans Amer Fish Soc 130: 1038-1048.
38. Richards JG, Heigenhauser GJF, Wood CM (2003) Exercise and recovery metabolism in the pacific spiny dogfish (*Squalus acanthias*). J Comp Physiol B 173: 463-474.
39. Brill R, Bushnell P, Schroff S, Seifert R, Galvin M (2008) Effects of anaerobic exercise accompanying catch-and-release fishing on blood-oxygen affinity of the sandbar shark (*Carcharhinus plumbeus*, Nardo). J Exp Mar Biol Ecol 354: 132-143.
40. Marshall H, Field L, Afiadata A, Sepulveda C, Skomal G, Bernal D (2012) Hematological indicators of stress in longline-captured sharks. Comp Biochem Physiol A 162: 121-129.
41. French RP, Lyle J, Tracey S, Currie S, Semmens JM (2015) High survivorship after catch-and-release fishing suggests physiological resilience in the endothermic shortfin mako shark (*Isurus oxyrinchus*). Conserv Physiol 3: cov044
42. Gallagher AJ, Serafy JE, Cooke SJ, Hammerschlag N (2014) Physiological stress response, reflex impairment, and survival of five sympatric shark species following experimental capture and release. Mar Ecol Progr Ser 496: 207-218.
43. Mandelman JW, Skomal GB (2009) Differential sensitivity to capture stress assessed by blood acid–base status in five carcharhinid sharks. J Comp Physiol B 179: 267-277.
44. Dicken ML, Smale MJ, Booth AJ (2006) Shark fishing effort and catch of the ragged-tooth shark *Carcharias taurus* in the South African competitive shore-angling fishery. Afr J Mar Sci 28: 589-601.
45. http://www.shellybeachskiboatclub.co.za/
46. Casselman SJ (2005) Catch-and-release angling: a review with guidelines for proper fish handling practices. Fisheries Section, Fish and Wildlife Branch, Ontario Ministry of Natural Resources.
47. Dunlop SW, Mann BQ (2013) An assessment of participation, catch and effort in the offshore boat-based linefishery in KwaZulu-Natal, South Africa. Afr J Mar Sci 35: 79-97.
48. Sink KJ, Holness S, Harris L, Majiedt PA, Atkinson L, et al. (2012) National Biodiversity Assessment 2011: Technical Report. Vol 4: Marine and Coastal Component. South African National Biodiversity Institute, Pretoria.
49. Lynch A-MJ, Sutton SG, Simpfendorfer CA (2010) Implications of recreational fishing for elasmobranch conservation in the Great Barrier reef marine park. Mar Freshw Ecosys 20: 312-318.
50. Götz A, Kerwath SE, Attwood CG, Sauer WHH (2007) Comparison of the effects of different linefishing methods on catch composition and capture mortality of South African temperate reef fish. Afr J Mar Sci 29: 177-185.
51. Prince ED, Ortiz M, Venizelos A (2002) A comparison of circle hook and "J"

hook performance in recreational catch-and-release. Amer Fish Soc Symp 30: 66-79.

52. Cooke SJ, Suski CD (2004) Are circle hooks effective tools for conserving freshwater and marine recreational catch-and-release fisheries? Aquat Conserv Mar Freshw Ecosys 14: 299-326.

53. Suski SJ, Barthel BL, Suski CD, Siepker MJ, Philipp DP (2005) Influence of circle hook size on hooking efficiency, injury, and size selectivity of bluegill with comments on circle hook conservation benefits in recreational fisheries. North Amer J Fish Manage 25: 211-219.

54. Afonso AS, Hazin FHV, Carvalho F, Pacheco JC, Hazin H, et al. (2011) Fishing gear modifications to reduce elasmobranch mortality in pelagic and bottom longline fisheries off Northeast Brazil. Fish Res 108: 336-343.

55. Afonso AS, Santiago R, Hazin H, Hazin FHV (2012) Shark bycatch and mortality and hook bite-offs in pelagic longlines: Interactions between hook types and leader materials. Fish Res 131: 9-14.

56. Pacheco J, Kerstetter D, Hazin F, Hazin H, Segundo R, et al. (2011) A comparison of circle hook and J hook performance in a western equatorial Atlantic Ocean pelagic longline fishery. Fish Res 107: 39-45.

57. Coelho R, Bentes L, Goncalves JMS, Lino P, Ribeiro J, et al. (2003) Reduction of elasmobranch by-catch in the hake semipelagic near-bottom longline fishery in the Algarve, Southern Portugal. Fish Sci 69: 293-299.

58. Myers RA, Worm B (2003) Rapid worldwide depletion of predatory fish communities. Nature 423(6937): 280.

59. Worm B, Davis B, Kettemer L, Ward-Paige CA, Chapman D, et al. (2013) Global catches, exploitation rates, and rebuilding options for sharks. Mar Policy 40: 194-204.

60. Clarke SC, McAllister MK, Milner-Gulland EJ, Kirkwood GP, Michielsens GJ, et al. (2006) Global estimates of shark catches using trade records from commercial markets. Ecol Lett 9: 1115-1126.

61. Heithaus MR, Frid A, Wirsing AJ, Worm B (2008) Predicting ecological consequences of marine top predator declines. Trends Ecol Evol 23: 202-210.

62. Heithaus MR, Frid A, Vaudo JJ, Worm B, Wirsing AJ (2010) Unraveling the ecological importance of elasmobranchs, In: Sharks and Their Relatives II: Biodiversity, Adaptive Physiology, and Conservation. Carrier J, Musick J, Heithaus M (eds) CRC Press, Boca Raton, FL, pp 608-633.

63. Estes JA, Terborgh J, Brashares JS, Power ME, Berger J, et al. (2011) Trophic downgrading of planet Earth. Science 333: 301-306.

64. Ripple WJ, Estes JA, Beschta RL, Wilmers CC, Ritchie EG, et al. (2014) Status and ecological effects of the world's largest carnivores. Science 343(6167): 1241484.

65. Gallagher AJ, Hammerschlag N (2019) Global shark currency: the distribution, frequency, and economic value of shark tourism. Curr Issues Tour 14: 797-812.

66. Cooke SJ, Suski CD (2005) Do we need species-specific guidelines for catch-and-release recreational angling to conserve diverse fishery resources? Biodiv Conserv 14: 1195-1209.

67. McGrath MD, Horner CCM, Brouwer SL, Lamberth SJ, Mann B, et al. (1997) An economic valuation of the South African linefishery. Afr J Mar Sci 18: 203-211.

68. Pradervand P, Baird D (2002) Assessment of the recreational linefishery in selected Eastern Cape estuaries: trends in catches and effort. Afr J Mar Sci 24: 87-101.

69. Molina JM, Cook SJ (2012) Trends in shark bycatch research: current status and research needs. Rev Fish Biol Fish 22: 719-737.

70. Lewison R, Crowder LB, Read AJ, Freeman SA (2004) Understanding the impacts of fisheries bycatch on marine megafauna. Trends Ecol Evol 19: 598-604.

71. Broadhurst MK, Kennelly J, Gray C (2007) Strategies for improving the selectivity of fishing gears In: By-catch Reduction in the World's Fisheries. Kennelly S (ed), Springer, Dordrecht, pp 1-21.

72. Hall MA, Dayton LA, Metuzas KI (2000) By-catch: problems and solutions. Mar Poll Bull 41: 204-219.

73. Horodysky AZ, Cooke SJ, Graves JE, Brill RW (2016) Fisheries conservation on the high seas: linking conservation physiology and fisheries ecology for the management of large pelagic fishes. Conserv Physiol 4: cov059.

74. Dudley SF, Simpfendorfer CA (2006) Population status of 14 shark species caught in the protective gillnets off KwaZulu-Natal beaches, South Africa, 1978-2003. Mar Freshw Res 57: 225-240.

75. Dicken ML, Hosking SG (2009) Socio-economic aspects of the tiger shark diving industry within the Aliwal Shoal marine protected area, South Africa. Afr J Mar Sci 31: 227-232.

76. Brett MR (2019) An assessment of coastal tourism amenities for the South Coast region, KwaZulu-Natal, South Africa. Afr J Hospitality Tour Leisure 8: 1-4.

77. Sink K (2016) The marine protected areas debate: implications for the proposed Phakisa marine protected areas network. S Afr J Sci 112: 1-4.

Author Affiliations

Top

[1]*Department of Mathematics & Statistics, University of West Florida, Pensacola, Florida, USA*
[2]*Shark Research Institute, Princeton, NJ 08542, USA*