SHORT COMMUNICATION

Forensic-Based and Environmentally Responsible Protocol to Manage Shark Fatal Bites on Humans Can Better Contribute to Conservation Needs

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ABSTRACT

Although sharks are important for marine ecosystems, they still suffer culling campaigns after human fatalities. A case study from the Caribbean shows how the rapid use of several complementary and reproducible forensic techniques not only allowed the confirmation of the species implicated in the bite but also the accurate assessment of the size of the animal. Six non-lethal fishing sessions led to the capture of several shark individuals that were released after either being eliminated due to their unsuitable size or the absence of human remains in their stomach. Such an ecologically responsible risk management can contribute to shark conservation.

1 | Introduction

Shark bites on humans average about 100 per year worldwide, with less than 10% resulting in death (Midway, Wagner, and Burgess 2019). Although rare, these events are generally given excessive media coverage, which amplifies the public's perception of risk (Crossley et al. 2014). Although heterogeneous in their duration, shark biting episodes are frequent and sometimes have significant repercussions on local blue economies, as is the case on the French island of Reunion (Indian Ocean) where financial losses in the eco-tourism sector have been estimated at several million euros per year from 2013 until the end of the decade, triggered by a series of biting events (Clua et al. 2020). The most objective possible assessment of the risk is therefore particularly relevant to inform policy makers in their management choices and requires precise identification of the species involved and a thorough understanding of the reasons for bites on humans, which are themselves deduced from a meticulous forensic and ecological analysis of the characteristics of the incident (Ritter and Levine 2004).

In terms of risk management, and although they have not proven to be fully effective in the past (Wetherbee, Lowe, and Crow 1994), culling fishing campaigns are still the most common way for public authorities to attempt to reduce the risk of human bites (Ferretti et al. 2015). Such methods are not only ineffective in reducing the risk but are unethical and environmentally impactful (Clua et al. 2020), as the chronic and indiscriminate removal of dozens or even hundreds of randomly selected individuals has a significant deleterious impact on the shark species directly concerned which are typically Red-Listed under the International Union for Nature Conservation. These blind fishing campaigns also include numerous by-catch species that are also vital for the overall marine ecosystem health and should therefore be better managed (Cliff and Dudley 2011). As it has been demonstrated for terrestrial predators (Swan et al. 2017), human–wildlife conflicts may often rely on a few individuals with atypical behaviour and qualified as ‘problem-individuals’ (Clua et al. 2024a). It is highly likely that this phenomenon can be extrapolated to shark risk management in the marine realm, promoting the hypothesis that an animal that has already bitten has a significantly higher propensity to do it again than its conspecifics that have never done so (Clua and Linnell 2019). Risk management in the context of human–wildlife conflicts in the marine environment would then probably benefit greatly from being inspired by approaches implemented in the terrestrial environment where, for example, the culling of big cats responsible for several fatal attacks on humans is generally addressed at the individual level within a given species (Krafte Holland, Larson, and Powell 2018) and not, as for sharks, at the level of an entire taxon, sometimes even without discrimination of the species involved. This lethal harvesting of sharks in the context of agonistic interactions with people comes on top of overfishing and bycatch of these animals (Queiroz et al. 2019), which play a crucial role in marine ecosystems (Dedman et al. 2024). As such, alternatives to unnecessary shark fishing must be explored (Meeuwig and Ferreira 2014).

Here, we use the case of a fatal shark bite on a French tourist on the island of Saint-Martin (French West Indies), in December 2020, to show how the rapid use of several complementary and reproducible forensic techniques not only allowed the confirmation of the species implicated in the bite but also the accurate assessment of the size of the animal, to support ecologically responsible risk management based on non-lethal fishing to identify the biting animal and limit any potential cull to that single individual.

2 | Material and Methods

2.1 | Data Collection

In the course of the investigation, one of the authors was summoned as an expert by the local French authorities in Saint-Martin and had access to the police report as well as the photos taken at the hospital during the treatment of the victim. He was also able to directly interview the professional ecotourism operator that found the body of the victim.

2.2 | Incident Background

On 10 December 2020, at approximately 1:45 PM, a French female tourist aged 30 years was swimming alone on the surface of a sandy bottom at a depth of approximately 6 m, about 250 m from the beach of Orient Bay beach on the North-East side of the island of Saint-Martin (see ESM 1) when she was attacked by a shark. The weather was fine with bright sunshine, almost no wind and clear water with about 20 m visibility. The beach was almost deserted but a person present at the scene heard cries of distress which led her to alert the manager of a water sports club who, accompanied by one of his work colleagues, boarded a 3.8 m inflatable with an outboard motor to go to the area where the distress cries originated. Having spotted a body floating on the surface with its head facing down, they approached the motionless body. As his companion jumped into the water to retrieve the body, the captain clearly observed a shark <2 m away from the boat, estimated to be between 2.5 and 3.0 m in length, “unquestionably smaller than the 3.8 m long boat”, swimming calmly towards the body at a depth of approximately two meters. According to the witness, the shark was dark in colour, with an elongated body and a “square” head, “characteristic of a tiger shark (*Galeocerdo cuvier)* “. After the assistant had made his way aboard the boat, they hoisted the body onto the boat and returned to the beach, where it was examined by a medical team. Interviews with people present at the time of the incident regarding events close to the time of the incident highlighted the presence of fish jumping to the surface, as if chased by a predator, the presence of a school of bottlenose dolphins – usually never seen at this location – and one diver reported the sighting of a large barracuda of approximately 1.4 m in length in the shelter of a floating pontoon close to the site of the attack.

2.3 | Shark Species Assessment

In order to better evaluate the impact of bites on the skeleton, the victim's body was examined post-mortem through a General Electric scanner 64b operated by one of the authors. During the manual autopsy of the body, photographs of the wounds including a metric marker were taken. The general and specific characteristics of the bite wounds were analysed and compared with anatomical data compiled for each species of large shark capable of inflicting such wounds on a human (Clua and Reid 2018). In the event that a complete shark tooth or a tooth fragment is found in the victim's wounds, it is processed for genetic analysis. DNA is extracted from the tooth using the Wizard Genomic DNA purification kit (Promega) following manufacturer instructions. DNA extraction quality is visualized on a 1% agarose gel. Taxonomic identification (barcoding) is performed using the 250 bp CO1shark25F – CO1shark315R fragment (CO1shark25F -5′ AGCAGGTATAGTTGGAACAGCCC 3′ and CO1shark 315R -5′ GCTCCAGCTTCTACTCCAGC 3′). Mitochondrial sequences are amplified using Qiagen reagents kit, with 2.5 μL Tampon TAQ 10X, 2 μL MgCl2 25 mM, 2.5 μL dNTPs 2 mM, 0.6 μL of each primer (10 μM), 0.1 μL Taq polymerase (5 μ/μL), Ultra-Pure H2O, 5 μL QSolution, for a final volume of 25 μL. PCR programs consisted of an initial denaturing step at 95°C for 3 min, followed by 40 cycles of 95°C for 30 s, 62°C for 45 s, and 72°C for 30 s, finished by 10 min at 72°C and then held at 4°C (Thermocycler Eppendorf nexus gradient). PCR products are all ran on a 2% agarose gel. PCR products are sequenced by GenoScreen (Lille – France) using an Applied Biosystem's 3730xl DNA Analyser. Sequence data are analysed with BioEdit 7.2.5 and exported to the BLAST function (fasta format) from GenBank.

2.4 | Shark Size Assessment

To assess the size of the animal, specific photographs focusing on the characteristic marks left by the teeth in unfinished and superficial bites, are used. The centre point of each of the mini-wounds left by the tooth is used to measure the interdental distance (IDD) between two tooth tips; these measurements are then averaged and the result is processed by a specific algorithm to determine the total length of the animal which is closely correlated with the IDD (Lowry et al. 2009).

3 | Results

3.1 | Description of the Wounds

The victim was bitten several times, with a particular focus on the right leg, the upper part of which at thigh level bore the stigmata of a very deep and disfiguring bite, with significant loss of flesh. The same leg was severed at the knee, revealing the lower joint of the femur (see ESM 2A). More superficial bites affected the victim's right hand (see ESM 2B) and left foot (see ESM 2C-D), suggesting the possibility of defensive and evasive action by the victim.

3.2 | Assessment of the Shark Species

The interview with the main witness confirmed a credible expert identification of a tiger shark. This identification was confirmed by visual analysis of the wound lips, which were straight and had small flaps consistent with a jaw composed of relatively closely spaced and well-aligned teeth, typical of a tiger shark (Clua and Reid 2018). The CT scan examination also detected the presence of a small foreign body (<0.5 cm) identified as a shark tooth fragment located near the proximal end of the victim's right femur (Figure 1). Mitochondrial DNA was extracted from this fragment and a genetic taxonomic identification was performed with a match score $>98\%$ for a tiger shark.

3.3 | Assessment of the Size of the Shark

A mean interdental distance (IDD) of 19.3 mm could be calculated from five measurements (Figure 2), resulting in an algorithmically (Lowry et al. 2009) estimated total animal length of 2.9 m TL.

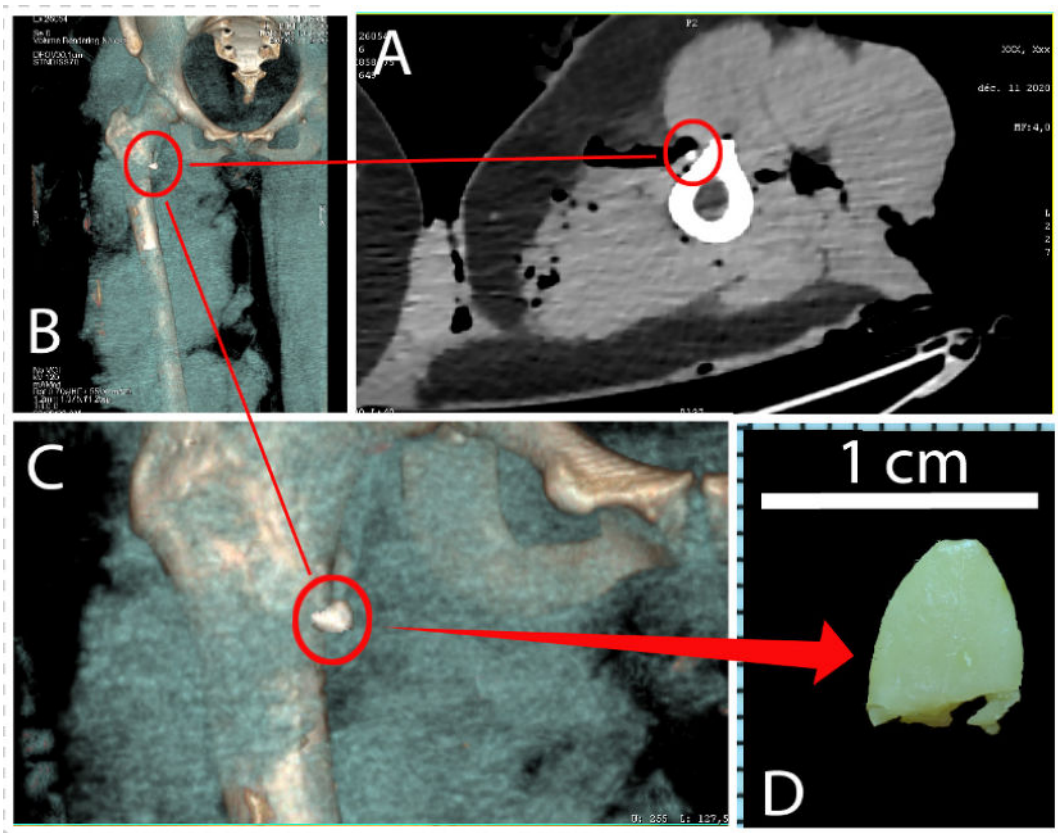

FIGURE 1 | (A) Scanner acquisition, without injection, with reformat reconstructions showing a 2D section in the soft tissue window including a foreign body of "hounsfield density" denser than human bone, identified as a fragment of shark tooth. This foreign body is located opposite lacerations as evidenced by pathological subcutaneous emphysema opposite the adjacent muscle planes. (B/C) 3D Virtual Reality (volume rendering) reconstruction in order to see the foreign body in space and to guide the forensic scientist's investigation (C = B with enlargement). (D) Close up on the piece of shark tooth corresponding to a tangential chip in the lateral part of the crown.

3.4 | Shark Non-Lethal Fishing and Discriminative Protocol

Non-lethal shark fishing was carried out with drumlines consisting of a large barbless hook mounted on a steel cable attached to a line hooked to a system of incompressible buoys that are anchored on the sea bottom. The hooks were baited with beef to limit the bait's attractiveness to other shark species. Lines were set on the surface on bottoms greater than 15 m to limit the ability of animals to rub against the substrate; they are deployed in the evening at dawn and visited at daybreak to limit the risk of exhaustion of caught sharks (approx. soaking time of 9–10 h). In order to increase the chances of catching tiger sharks, eight drumlines were deployed during each fishing session in the Anguilla Channel, in an area that is conducive to the passage of large sharks on the fringes of anthropogenized coastal areas (ESM 1). If a shark is present, it is taken and pulled alongside the boat, or even taken on board if it is < 2 m in size. The animal is measured through total length (TL), the sex identified by the presence or absence of claspers, and a genetic sample is taken in the form of a skin biopsy. If the animal's size is outside the range of the TL size assessed by forensic analysis with an error margin of +/−10% of TL, the animal is immediately released. If the animal's size falls within the size range, the animal is placed in tonic immobility (Kessel and Hussey 2015) and undergoes a stomach search to identify the presence of human remains, in the form of undigested flesh or bone. Stomach exploration through flushing (Barnett et al. 2010) is carried out by connecting a hose to an electric pump that allows the animal's stomach to be filled rapidly through the mouth and oesophagus. Once the stomach is filled, gentle pressure is applied to the stomach wall to induce vomiting and regurgitation of the stomach contents, which are collected in a bucket. If human remains, especially bones, are identified, the animal would be euthanized with Eubutramid (75 mg/kg) via an intravenous line to the caudal vein.

3.5 | Non-Lethal Fishing Campaign

Six non-lethal fishing sessions took place between 8 January and 21 February 2021, resulting in the capture of 24 tiger sharks, including three males and 21 females, measuring between 109 and 400 cm in total length (TL) (Table 1). Of these animals, only two female individuals captured on 21 February had sizes compatible with the forensic size assessment of 2.9 m TL (280 and 284 cm TL, respectively). Both animals underwent stomach exploration which proved negative and were also released.

4 | Discussion

4.1 | Potential Role of Anthropause in the Shark Incident

The observation of repeated bites resulting in a significant loss of tissue and bones, including half of the victim's right leg, combined with the involvement of a highly traumatogenic

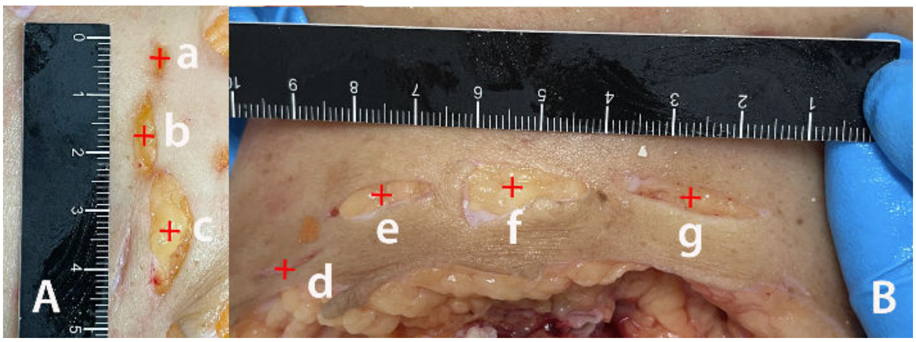

FIGURE 2 | (A) Impressions left by three contiguous teeth resulting in the measurement of two interdental distances of [ab] = 16 mm and [bc] = 21 mm. (B) Impressions left by four contiguous teeth leading to the measurement of three interdental distances of [de] = 18 mm, [ef] = 19 mm and [fg] = 26 mm. The red crosses correspond to the centre of the imprints corresponding to the tips of the shark's teeth.

TABLE 1 | Distribution of animal captures during the six fishing sessions with indication of gender and the total length of each individual. Animals marked with an * fit with the forensic size assessment and underwent stomach exploration.

Fishing session	#1	#2	#3	#4	#5	#6	TOTAL catch
Date	08/01/2021	24/01/2021	29/01/2021	04/02/2021	11/02/2021	21/02/2021	
Female (size cm)	230, 350	109, 330,400	121, 157, 177, 179, 234, 275	109, 231, 350	264	214, 224, 264, 273, 280*, 284*	21
Male (size cm)	190	128, 131					3
Total	3	5	6	3	1	6	24

species, leaves no doubt that the bite motive was predation with an animal seeking to feed on a human being (Ihama et al. 2009). The victim probably died of cardiovascular collapse as a result of massive external bleeding caused by the bites on the right leg. It is likely that without the intervention of the boat, the shark would have continued to feed upon the cadaver of the victim. The likelihood of a human inadvertently interacting with a large shark that might consider it as potential prey is extremely low, especially in the Caribbean where such incidents are extremely rare (in the order of one or two per decade), with the last such incident being the death of a 21-year-old American girl attacked by a tiger shark in Pig Island, Bahamas, in June 2019 (The NZHerald 2019). As this is primarily an issue of the probability of encounters between potentially dangerous animals and potential human prey, as demonstrated in Australia (West 2011) and the USA (Ferretti et al. 2015), the only factor that could have contributed to the St. Martin incident is the 2020 anthropause, which drastically reduced anthropogenic activities in the Orient Bay area that likely have a chronic expulsion effect on marine species that are cautious towards human and their activities. Just as large predators such as mountain lions *Puma concolor* have taken advantage of the COVID-linked lockdown to move back into areas normally frequented by humans (Wilmers, Nisi, and Ranc 2021), tiger sharks – whose density seems to be quite high in the Anguilla channel given the high catch rate (see Table 1) – have likely increased their use of the waters of this bay in 2020, as has been observed for bottlenose dolphins which are also usually not present in this area (C. Lucidarme, Pers. Comm.). This context of a significant and extended absence of human activity in the bay prior to the incident may have indirectly increased the probability of this agonistic encounter, as shown for coastal sharks in French Polynesia (Clua et al. 2024b). In contrast, the absence of turbid water or wind that could blur visibility, the time of day (far from dusk), all of which are environmental factors generally considered to be contributing and/or explanatory factors for shark bites on humans (Chapman and McPhee 2016; Midway, Wagner, and Burgess 2019; Ryan et al. 2019), but are all absent and non-contributory factors in the current report. This case reinforces the hypothesis that the individual behavioural component, of this individual shark, is likely to be the dominant factor compared to secondary environmental factors in the context of predatory bites on humans (Clua and Linnell 2019).

4.2 | An Efficient Combination of Forensic Approaches

Perhaps the most innovative aspect of this study was the combination of several forensic approaches to determine as quickly as possible not only the species of shark responsible for the bite, but also the size of the individual involved. The use of a CT scan for forensic purposes was recently suggested and indeed proved to be an invaluable asset (Byard and Perumal 2024). Prior to the autopsy itself, it allowed for the early identification of a fragment of shark tooth that would probably have gone unnoticed without this exploratory approach. Having a pinpoint location for the fragment allowed it to be extracted and used for genetic analysis, which confirmed the identification of the species. Furthermore, the use of the mean interdental distance (IDD) technique led to a relatively accurate assessment of the size of the shark, with the linear-regression based algorithm (Lowry et al. 2009) considered to be reliable for tiger sharks (Stock, Winburn, and Burgess 2017). This is crucial as it allowed for the implementation of a non-lethal fishing approach that resulted in the capture of 24 animals within eight weeks of the incident, without any of them being unnecessarily sacrificed. While the exploration of the stomachs of two sharks took place several weeks after the bites, human bones are known to remain in shark's stomach for extended periods of time (Işcan and McCabe 1995), which allows us to assume that in this case it would be highly likely that large bones such as the victim's tibia would still have been visible if one of the two sharks was responsible for the attack. It is worth noting here the high propensity of large sharks for natural and harmless stomach eversion (Hammerschlag and Sulikowski 2011), in particular for tiger sharks, which constitutes a major asset for the implementation of our proposed protocol. However, non-lethal fishing should be carried out as soon as possible after the incident. We also believe that the stomach flushing technique applied to animals whose size is comparable to that of the biting shark, which is often difficult to implement, could be advantageously replaced by an easier to implement, exploration based on either ultrasound, which has been routinely practiced in sharks previously (Walsh et al. 1993) or on radiography based on waterproof-adapted large devices.

How we successfully manage future fatal shark attacks on humans can, in part, be guided from previous strategies that have been largely implemented following impulsive decision-making made during the obvious heightened emotional state of policy makers, and the public, in the aftermath of such highly publicized/reported events. In the French overseas island territory of Reunion (Indian Ocean) five fatal bites by bull sharks took place between 2010 and 2013. The subsequent indiscriminate culling of sharks, irrespective of size or species, led to the removal of 780 sharks (595 tiger sharks and 185 bull sharks) between 2013 and October 2024; however, this did not prevent six new fatal bites occurring, two fatalities occurring in each of the years 2015, 2017 and 2019 (CRA 2022; CSR 2022). Such environmentally impactful measures could have been avoided if a more forensic approach, as detailed herein, combined with non-lethal fishing had been implemented.

4.3 | Implications to Conservation

Here we describe a more scientific and conscientious approach for identifying an individual problem shark following a fatal predatory attack on a human. Ideally, the methodologies described herein would be implemented immediately following such an event and not days to weeks after. If such an approach can be agreed upon as the initial and primary response to shark attacks on humans, it can become a routine emergency response to these unfortunate events. Historically, the indiscriminate culling of sharks in the surrounding areas, following such events, has not decreased the chances of additional shark attacks on humans and has resulted in the unnecessary removal of hundreds of sharks (Clua et al. 2024a). Our forensic approach should include the following components if logistically possible and local circumstances allow:

- Early swabbing of wounds on the victim in order to potentially identify the shark species and the individual's profile through DNA transfer (see Clua et al. 2020).
- Interview witnesses to assist with identification of the species, based on visuals, shark features (size, colour, shape, etc.) and behaviour (see Clua and Reid 2018).
- Examination of the survivor or the remains for estimates to be made on the species using features of the wounds (see Clua, DeMarchi, and Reid 2024c) and size of the individual shark using IDD technology (see Lowry et al. 2009).
- Use tomography and other imaging techniques to examine wounds for tooth fragments for genetic identification of the individual shark (see Byard and Perumal 2024).
- Begin rapid non-lethal fishing as soon after a shark biting episode as possible (this study).
- Use of stomach exploration through assisted vomiting or imaging techniques such as ultrasound or radiography to confidently access the stomach contents (and potential human remains) of sharks caught that fall within the target size defined by the IDD analysis and allow a very selective culling of the biting shark (this study).

Whether individual genetic profiling (Clua et al. 2020) or stomach exploration by radiography (this study) are concerned, these techniques, commonly used on land – particularly for humans – are not yet fully democratized and easily accessible for animals in the marine environment. Nevertheless, they should become so, in order to contribute to the conservation challenges linked to effective alternatives allowing the ban of deleterious strategies of indiscriminate mass shark culling.

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Ethics Statement

The access to the victim's body was allowed under the permit ref# P.V. n° 02351/2020 from the Cellule d'Identification Criminelle de SAINT-MARTIN 978. This study was conducted under the official "Attestation d'Action en Gestion de crise" of the Public High Commissioner Office of Saint-Martin Ref. *N°SXMPREF/COD/1001/2021 du 19 juillet 2021*.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.