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When prey becomes killer: does a double lethal attack on a blue shark reveal a precise defensive strategy in young swordfish?

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Abstract

In this paper a rare case of a double swordfish mortal attack against an adult blue shark (*Prionace glauca*) is reported. A female blue shark, with a total length of 3 m, was found stranded along the southern Sicilian coast (Strait of Sicily, Mediterranean Sea) on 30 May 2018. The analysis of this carcass revealed the presence of two swordfish bill fragments, impaled in the shark head; the former on the snout, the latter near the eye. The results of anatomical and computed tomography scanning analysis on the head of the blue shark showed that the larger bill fragment (19.7 cm) probably determined the death of this animal, having been impaled in a vital point, just behind the right eye. The analysis of both these events and other similar swordfish-shark interactions reported in the literature makes possible the hypothesis that young swordfish specimens put in place a precise defensive strategy against their potential predators or competitors, aimed at hitting vulnerable and vital points and delivering a mortal blow.

Introduction

The blue shark, *Prionace glauca* (Linnaeus 1758), and swordfish, *Xiphias gladius* Linnaeus 1758, are two large pelagic and highly migratory predators sharing the same habitat, as demonstrated by the frequent incidence of this shark in the by-catch of drifting longlines targeting swordfish (De Metrio *et al.*, 1984; Megalofonou *et al.*, 2005, 2009; Campana *et al.*, 2009; Garibaldi, 2015*a*). The blue shark is a cosmopolitan species distributed in temperate and tropical waters of all oceans (Nakano & Seki, 2003). Satellite tagging data demonstrated that it can be found from the surface to a maximum depth of 350 m (Stevens *et al.*, 2010). However, the blue shark is more common in epipelagic waters (Nakano & Seki, 2003), spending most of the time in upper waters and only little time at depths more than 350 m (Stevens *et al.*, 2010; Ebert *et al.*, 2013). This depth range partially overlaps with the vertical distribution of swordfish, this teleost fish being able to perform large vertical excursions. Indeed, swordfish occurs from deep waters (up to 2887 m, according to Collette *et al.*, 2011; but usually between 400 and 800 m, Lerner *et al.*, 2013), where it prefers to stay during the day, towards upper layers during the night (Carey & Robinson, 1981; Carey, 1990; Takahashi *et al.*, 2003; Lerner *et al.*, 2013). According to Canese *et al.* (2008), the swordfish permanence in deep waters is frequently interrupted by vertical rises. This behaviour changes in late spring and summer, during the reproductive period, when swordfish prefers to spend more time in surface water layers for mating (Romeo *et al.*, 2009, 2011b, 2015; Battaglia *et al.*, 2018) and, then, the possibility to meet the blue shark increases. Moreover, available data on swordfish catches by conventional surface longline and mesopelagic longline demonstrate that smaller individuals are more abundant in upper waters (Garibaldi, 2015*b*), increasing the chance of interacting with the blue shark.

Although the profile of vertical distribution of both blue shark and swordfish also depends on environmental factors (Bigelow *et al.*, 1999; Damalas & Megalofonou, 2010; Stevens *et al.*, 2010; Lerner *et al.*, 2013; Braun *et al.*, 2015), an important role in these movements is played by food distribution in the water column (Bigelow *et al.*, 1999; Stevens *et al.*, 2010) and prey aggregations at water fronts may represent an attraction for these predators (Bigelow *et al.*, 1999). Albeit the blue shark also displays an opportunistic feeding behavior for carrion, such as seabirds or marine mammals (Compagno, 1984; Stevens, 2009), the diets of blue shark and swordfish partially overlap, in particular for pelagic cephalopods and some fish prey (Bello, 1996; Clarke *et al.*, 1996; Romeo *et al.*, 2011*a*; Hernandez-Aguilar *et al.*, 2015).

Fig. 1. The female blue shark, 3 m total length, found stranded along the southern Sicilian coast (Strait of Sicily, Mediterranean Sea) on 30 May 2018.

Moreover, the diet of the blue shark also includes juvenile swordfish (Vaske-Júnior *et al.*, 2009; Lopez *et al.*, 2010; Markaida & Sosa-Nishizaki, 2010). The predator–prey interactions, competition and habitat use sometimes generate conflicts between swordfish and sharks, as already demonstrated by some documented swordfish attacks towards elasmobranchs (Starck, 1960; Vacchi *et al.*, 2000; Ellis, 2013; Penadés-Suay *et al.*, 2017, 2019). This swordfish aggressive behaviour has also been documented against other large pelagic animals (e.g. whales and turtles), objects, ships, boats, fishing vessels, humans (e.g. Gudger, 1938, 1940; Frazier *et al.*, 1994; Zarudski and Haedrich, 1974; Georgiadou *et al.*, 2010; Ellis, 2013; Romeo *et al.*, 2017) and even other swordfish (Carey & Robinson, 1981).

In this paper a rare case of a double swordfish mortal attack to an adult blue shark is reported. The blue shark was found stranded along the southern Sicilian coast (Strait of Sicily, Mediterranean Sea) and analysis of its carcass revealed that the specimen was impaled by two swordfish bills. The analysis of both our case study and data available in the literature seems indicate a precise defensive strategy by young swordfish individuals, discussed in this paper.

Materials and methods

On 30 May 2018 a large shark was found stranded on the beach in Borgo Bonsignore (37°24′56.55″ N 13°15′54.50″ E), along the southern Sicilian coast (Strait of Sicily, Mediterranean Sea). The specimen was identified as a blue shark. It was a female individual of about 220 kg, measuring exactly 3 m total length (Figure 1). The carcass management procedures for the inspection and removal of the specimen were activated by the local Authority. The blue shark's body was inspected in order to understand the reasons of the death and, in particular, if it had been directly or indirectly caused by human activities (fishing, ingestion of marine litter, boat collision etc.). Two bill fragments were found pierced in the head of the blue shark and they were considered to belong to two different individuals of swordfish, according to the features described by previous studies (Fierstine & Voigt, 1996, Penadés-Suay *et al.*, 2017, 2019): (i) flattened appearance in cross-section (i.e. depth less than half of width); (ii) absence of denticles on the surface; (iii) presence of central chambers in cross-section.

After having observed that the head of this animal had been injured by swordfish, a radiology survey was performed on the blue shark's skull by X-ray computer-assisted tomography through two CT scans (Philips Brilliance 16 Slice CT Scanner): a first axial non-volumetric scan, having caudal-snout direction and 3 mm thickness cross-sections and a second volumetric scan, having snout-caudal direction and 2 mm thickness cross-sections.

The CT scans were elaborated via 3D method through post-processing Volume Rendering technique (VR), Maximum Intensity Projection (MIP) and Multi-Planar Reconstruction (MPR). This exam was performed at the 'Centro di Radiologia Diagnostica' in Sciacca (Italy).

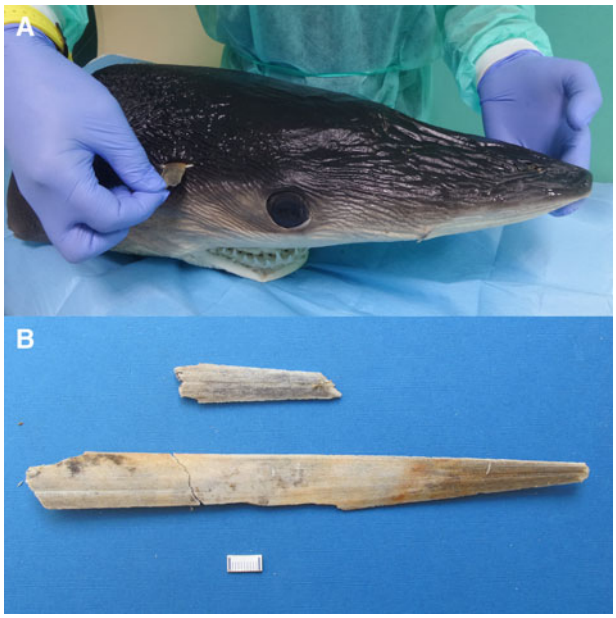

Fig. 2. (A) The phase of the extraction of the longer bill fragment stuck behind the right eye of the blue shark; (B) the two swordfish bill fragments extracted from the head of the blue shark.

Results

At first inspection, the stranded blue shark did not show any visible sign of evident cut, wounds or contusive trauma, or injuries from fishing gear interactions (hooks, lines, nets). The body of the fish showed no signs of decomposition: the bright colour of gills and the brightness of the eyes indicated that the specimen's death and beaching had happened a few hours previously, probably during the night. However, after a careful examination, two small cut lesions were observed and two rostra of swordfish were found stuck in the head of the blue shark (Figure 2):

(i) The first small cut was on the snout of the blue shark; from this cut a few millimetres of bone fragment protruded outside and after its extraction it was recognized to be the apex of a swordfish bill, 7 cm long (Figure 2B). Although this bill was stuck near the olfactory encephalic bulb, it could hardly have caused the death of that animal.
(ii) Another small cut was observed behind the right eye of the blue shark. In this case no objects were observed protruding from the specimen's head. Inspection of this cut revealed the presence of another swordfish bill (Figure 2B), longer than the first one (19.7 cm). The death of the blue shark was probably determined by this last rostrum.

It is not clear if the blue shark was impaled by two swordfish during a simultaneous attack or in different periods. Epidermal, dermal and subcutaneous wounds were recent and characterized by the presence of serous drainage. Scar tissue, fibrin and hemosiderin were absent. Furthermore, adhesions among the animal tissues and the two swordfish rostrum fragments were not found. For these reasons, it is plausible that swordfish attacks to the blue shark occurred close in time.

The CT analysis (Figure 3) showed a good representation of cartilaginous tissues, but also soft tissues, in which it was possible

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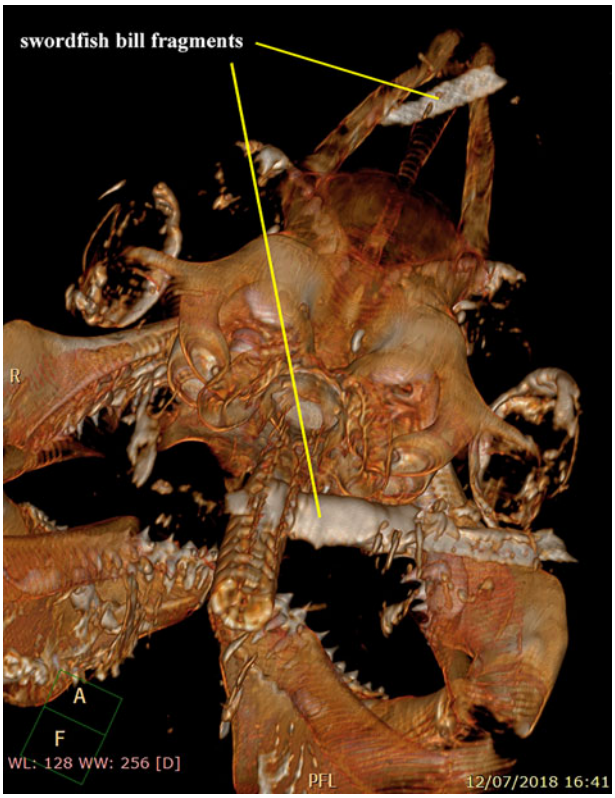

Fig. 3. An image obtained by a computed tomography analysis, showing the two bill fragments impaled into the blue shark's head.

to observe a widespread subcutaneous emphysema, not deforming anatomic shape. The smaller fragment of swordfish bill was located in the anterior left part of the shark snout, showing a homogeneous density (about 750 HU). This bill impaled the shark snout with antero-posterior, supero-inferior and latero-medial direction, penetrated without contact over the left cartilaginous component and ended into the contra-lateral component. This bill caused a little cut together with small bone and cartilaginous fragments production, but did not injure the shark's vital organs (Figure 3).

The larger swordfish bill fragment (19.7 cm; about 700 HU) was found in the prevertebral plane, near the left side craniodorsal tract (Figure 3). The bill penetrated with antero-posterior, infero-superior and latero-medial direction, piercing the soft tissues of left emisoma, tangentially to the postero-superior margin of the shark cranium, crossing the vertebral column (V–VI vertebra). Here some vertebral fragments in adjacent soft tissues can be observed by CT scans, without contact with the left cartilaginous component and ending into the contra-lateral component. This bill determined a little cut together with small bone and cartilaginous fragments production, but did not injure the shark's vital organs. The tip of this bill penetrated in medullary canal, partially destroying its lateral walls and causing a sub-total occlusion of the spinal canal for the presence of hyperdense material (1300 HU), extending in cranium-caudal direction for about 3.5 cm. The same hyperdense material was observed next to the tip of the bill as well as near vertebrae in contro-lateral position. The typology of this injury suggests that the impact provoked the immediate sectioning of medulla.

Discussion

The analysis of the stranded elasmobranch carcass allowed the recording of a double swordfish attack on a blue shark, confirming that the interaction between swordfish and blue shark is more common than is thought. The size and proportions of the bill fragments indicated that the perpetrators of these swordfish attacks were juvenile individuals, similarly to the other recent cases of swordfish attacks against the blue shark reported by Penadés-Suay *et al.* (2017, 2019). These authors firstly examined a large blue shark stranded on the Mediterranean Spanish coast of Valencia in September 2016 (Penadés-Suay *et al.*, 2017), and then reported four other cases of similar interactions (Penadés-Suay *et al.*, 2019). Another analogous attack was observed in the past by Vacchi *et al.* (2000) in the Tyrrhenian Sea, concerning a swordfish impalement in the intra-orbital region of a bigeye thresher shark (*Alopias superciliosus*). All the above-mentioned attacks were performed by juvenile swordfish (reconstructed total length of rostrum ranging between 24.2–50.5 cm) and the target was always the shark head, in particular around the orbital region (Appendix 1). In Appendix 1, we report a summary of these attacks including information on the bibliographic reference, date and location of the shark stranding, shark size, and the location and description of the injury determined by the impalement.

On the basis of these results as well as the current knowledge on swordfish and blue shark behaviour and ecology, it is possible to make some considerations in order to explain these attacks. From an ecological point of view, the interactions between swordfish and blue sharks may be mainly summarized in the following relationships:

(i) *Competition for food resources between top predators*: the partial overlap between the diets of the blue shark and the swordfish (Bello, 1996; Clarke *et al.*, 1996; Romeo *et al.*, 2011*a*; Hernandez-Aguilar *et al.*, 2015) may produce conflicts between these two species. Competition for food resources may also be exacerbated by the recent decrease or depletion of several prey stocks, also due to fishery overexploitation (Bearzi *et al.*, 2006). Swordfish may display an aggressive behaviour against sharks during foraging activity. The hypothesis of accidental collisions between swordfish and sharks during feeding activity on the same prey school (Fierstine *et al.*, 1997; Penadés-Suay *et al.*, 2017), already proposed by some authors to also explain turtles' impalement (Frazier *et al.*, 1994), can be excluded for the contemporary finding of two swordfish bills impaled in the same shark. Moreover, both attacks were directed to the shark cranial zone, as in all the other cases reported in the literature (Vacchi *et al.*, 2000; Penadés-Suay *et al.*, 2017, 2019) (Appendix 1);

(ii) *Predator–prey relationship*: data available in the literature show evidence of predation on juvenile swordfish by blue sharks (Vaske-Júnior *et al.*, 2009; Lopez *et al.*, 2010; Markaida & Sosa-Nishizaki, 2010). All records of impalement reported in Appendix 1 can be referred to an interaction between a juvenile swordfish (two in our study case) and a large shark (236–300 cm TL for *P. glauca*, 400 cm TL for *A. superciliosus*). This indicates that the most probable reason for these attacks is a defensive reaction from the juvenile swordfish to a shark attack or to the presence of a potential predator (the shark). These predator–prey interactions seem to trigger a precise defensive strategy in young swordfish, which consists in a counter-attack against the shark, trying to pierce its vital points (Appendix 1). The finding of two bill fragments in the head of the same blue shark (present study) may be related to two almost simultaneous attacks if both swordfish specimens were in the same area (e.g. during foraging activity on the same prey shoal). Otherwise, the swordfish attacks were carried out

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by two young individuals at different times and, in this case, we imagine that the injury provoked by the smaller bill fragment should be referred to as a first, not lethal attack.

(iii) *Occasional disturbance during swordfish reproductive period*: higher swordfish belligerency during the reproduction period is well documented (Romeo *et al.*, 2017). In particular, males (smaller in size) strenuously defend females during the reproductive period, also attacking fishing boats if disturbed (Romeo *et al.*, 2017). The shark may have disturbed a couple during their courtship and therefore was impaled by defensive reaction. In our specimen, we found two bill fragments impaled in the shark head and it could also be possible that the attack was performed by two males following the same female. Indeed, according to some authors (Sisci, 1984; Romeo *et al.*, 2015), during the swordfish reproductive period, it is possible to observe the presence of two males near the same female. However, the bill fragments seem to belong to juvenile swordfish specimens, also according to the available information on swordfish morphometric data (Uchiyama *et al.*, 1999; Habegger *et al.*, 2015) and size at first maturity (Macías *et al.*, 2005; Abid *et al.*, 2019). Thus, this hypothesis can be considered less probable.

Based on these considerations, finally, we can conclude it is very probable that swordfish juveniles counter-attacked the shark in a defensive reaction to an attack or simply due to the presence of a potential predator. In this case the swordfish defensive strategy aims to deliver a blow against shark vital points, such as the head or eyes. As in other cases previously reported (Penadés-Suay *et al.*, 2017, 2019), the angle of spearing suggests that the direction of attack was almost always nearly horizontal in regard to the anteroposterior axis of the blue sharks, then delivered with the aim to target these vital points. Large pelagic sharks are among the few natural predators of swordfish and billfishes in general, and they probably are seen as enemies or threats, as also confirmed by the fact that sharks regularly attack swordfish individuals caught by professional (with harpoon and longlines) or sport fishermen (Palko *et al.*, 1981). Aggressive behaviour against sharks was also observed by Cliff *et al.* (1990) in the sailfish *Istiophorus platypterus*, in the case of a shortfin mako *Isurus oxyrinchus* off South Africa with a broken bill embedded in the shark left orbit. Other cases of impaled sharks by swordfish or other billfishes have already been reported by Starck (1960), Fierstine *et al.* (1997) and Ellis (2013).

Clear proof of an interaction of a blue shark with two swordfish is reported for the first time in this paper (finding of two bill fragments impaled in the head of the shark), although Penadés-Suay *et al.* (2019) hypothesized a similar event in a blue shark stranded on the beach of Vera (Spain). Indeed, these authors found a swordfish bill fragment inside the right nostril, referred to an old injury, and then to a previous not deadly interaction with the blue shark, but also a mortal wound anteriorly to the right eye, without an associated bill fragment and possibly related to another swordfish attack (Penadés-Suay *et al.*, 2019). All swordfish attacks against blue sharks reported in the literature (see Appendix 1) seem to reveal a precise defensive strategy performed by juvenile swordfish, which aims to hit the shark by targeting the head region where vital organs are located. It also appears that swordfish attacks may be underestimated, as suggested by Penadés-Suay *et al.* (2019), since our data are based only on the inspection of stranded shark carcasses and non-mortal attacks are difficult to record and, in some cases, need particular scientific tools (e.g. computed tomography scanning).

Finally, the widespread use in the past of driftnets targeting swordfish probably contributed to the decline of the blue shark, which has been listed as near threatened in the IUCN Red List (Rigby *et al.*, 2019). However, in recent years, after a long period of serious stock depletion (Rigby *et al.*, 2019), the blue shark seems to be showing signs of recovery (Serena & Silvestri, 2018). This probably increases the chance of potential interactions with swordfish, as demonstrated by the recent records of swordfish attacks against the blue shark (Penadés-Suay *et al.*, 2017, 2019; present paper).

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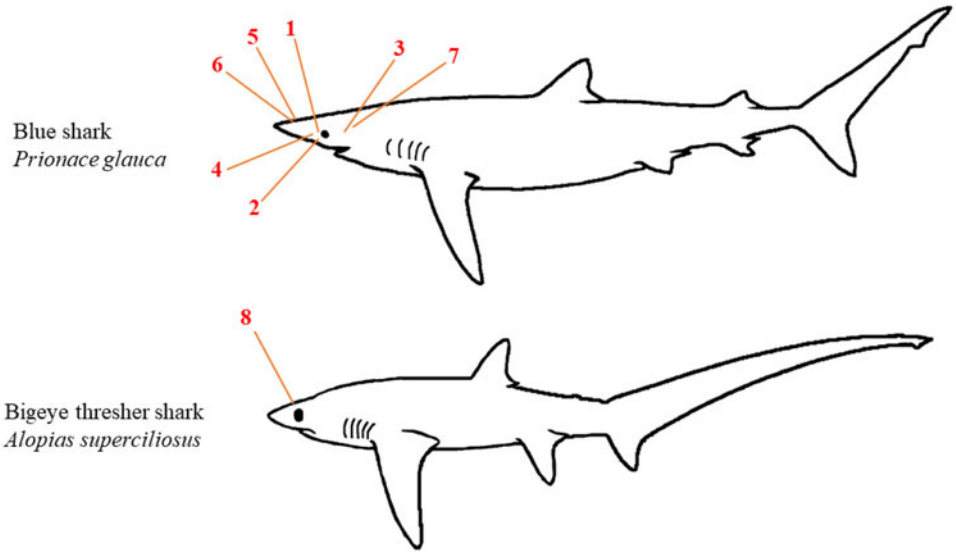
Appendix 1.



Appendix 1. Summary of recent swordfish attacks on sharks in the Mediterranean Sea, with a drawing showing where each impaled bill was found. Information on the bibliographic reference, date and location of the shark stranding, shark size, and a description of the injury determined by the impalement are provided.

Swordfish attacks against blue shark				
Record	**Reference**	**Date and Location**	**Shark size**	**Description**
1	Penadés-Suay *et al.* (2017)	September 2016, Valencia (Spain).	247 cm TL	An incision of 35 mm was found 11 mm anterior to the left eye (bill fragment: length 18 cm, width 3 cm proximally)
2	Penadés-Suay *et al.* (2019)	17 February 2017, Garrucha (Spain).	236 cm TL	The animal had an incisive injury between the left eye and the snout (bill fragment: length 18 cm, width 2 cm proximally)
3	Penadés-Suay *et al.* (2019)	8 March 2017, Ostia (Italy).	260 cm TL	An incision was visible between the first gill slit and the right eye (bill fragment: length 25 cm, width 3 cm proximally)
4	Penadés-Suay *et al.* (2019)	28 February 2018, Vera (Spain).	260 cm TL	A distal fragment of swordfish bill inside the right nostril, anterior to the firstly detected injury (bill fragment: length 5.3 cm, width 1.2 cm proximally). Another putative impalement injury anterior to the right eye but without an associated bill fragment
5	Penadés-Suay *et al.* (2019)	2 August 2018, Manacor (Spain).	293 cm TL	A distal fragment of a swordfish bill embedded in the snout (bill fragment: length 6.8 cm, width 1.5 cm proximally)
6	Present paper	30 May 2018, Borgo Bonsignore (Sicily, Italy)	300 cm TL	A bill fragment stuck near the olfactory encephalic bulb of the shark snout (bill fragment: length 7 cm, width 1.3 cm proximally)
7	Present paper	30 May 2018, Borgo Bonsignore (Sicily, Italy)	300 cm TL	A bill fragment stuck behind the right eye of the blue shark (bill fragment: length 19.7 cm, width 1.9 cm proximally)
Swordfish attacks against bigeye thresher shark				
Record	**Reference**	**Date and Location**	**Shark size**	**Description**
8	Vacchi *et al.* (2000)	November 1994, Tavolara Island (Sardinia, Italy)	400 cm TL	A mortal wound in the intra-orbital area of the head of the shark (bill fragment: length 15 cm)

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