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Contribution of Forensic Analysis to Shark Profiling Following Fatal Attacks on Humans

Eric Clua and Dennis Reid

Abstract

Size assessment and species identification are paramount after a fatal attack for profiling a 'problem-animal' that could be specifically eliminated. In addition to ecological and behavioural data about candidate species, forensic analysis can provide critical information for achieving this goal. After providing basic information about fatal attacks and the anatomical features of the three species (white shark, tiger shark and bull shark) that are responsible for >80% of lethal interactions, this chapter presents the most used tools for assessing the species and size of a potential attacker. The size assessment can be done through measurements (on the body of the victim or from good-quality photographs) of the bite width (BW) and bite circumference (BC); the size is then obtained from regressions from the literature between BW/BC and total length. The average interdental distance (IDD) is also used through a similar process. Finally, other details of the wounds, such as the shape of the bite margin or of flesh flaps that directly depend on the jaw characteristics, can also be used to contribute to the final assessment. Although important, a forensic analysis should be complemented by data on shark ecology and behaviour for a more reliable conclusion.

Keywords: agonistic behaviour, shark bites, wound analysis, species identification, interdental distance, attacker total length, flesh flaps

1. Introduction: why profiling of sharks?

Although shark populations are facing declines worldwide, recorded instances of unprovoked attacks by sharks on humans have been increasing in recent years, stirring public concern and generating radical policies such as blind culling. The annual average number of fatal attacks increased from 4.3 persons per year (2001–2010) up to an average of 8.0 persons per year between 2011 and 2015 [1]. Such an unexpected trend can mainly be explained by a significant increase of the number of sea users that increases the probability of encounter between these

marine predators and humans as shown in Australia [2]. In California, despite increasing records of white shark (*Carcharodon carcharias*) attacks, the individual attack risk for ocean users has decreased by >91% over a 63-year period (1950–2013) [3].

The triggers of shark attacks on humans are not well understood and still remain controversial. Such an understanding of attack motivation is jeopardized by the low number of attacks around the world, the scarcity of witnesses and the difficulty to observe an underwater event. A better understanding of shark motivations and behaviour through forensic analysis should at least partly help to avoid adverse outcomes in human encounters with these endangered creatures [4, 5]. If there is a witness to an attack, comparison of display features between the different species of potentially dangerous sharks can help in defining implications for shark-human interactions and suggests responses which may decrease the likelihood of attack for swimmers or divers faced with a postural display by a shark [6]. After the attack, the bite structure of the wounds may reflect the motivation and behaviour of the shark [7]. It can also allow the identification of the species involved in the attack and the accurate assessment of the animal size. The profiling (and potential elimination) of 'problem individuals' (see [8]) should be preferred to implementing inefficient blind culling of sharks (see [9]), whatever their species or size, as was recently the case in Western Australia and La Reunion island. In this French island of the Western Indian ocean, the decision to launch a culling campaign was adopted after five fatal attacks that occurred between 2011 and 2013; it not only removed tens of sharks (mainly tiger *Galeocerdo cuvier* and bull *Carcharhinus leucas* sharks) but also a white shark that was culled in October 2015, although this species is protected by international regulations. However, innovative solutions (to be set up in the near future) for spotting and eliminating the specific 'problem individuals' require early and efficient shark profiling after an attack.

The purpose of this chapter is to provide marine biologists or medical practitioners potentially involved in the postmortem analysis of a shark attack with the basic knowledge for assessing the species and size of a shark, based on bite features and tooth imprint. Our focus will remain on the data that should be collected and analysed from the wounds on a shark bite victim. This chapter does not include the ecological aspects (including life traits and behaviour of the sharks) which are a critical part of the holistic analysis of a shark attack in order to identify the shark species potentially involved in a fatal interaction. Neither does it include the problems that may appear when cadavers remain in the water for a significant period, creating several problems for diagnostics as shown by [10], nor forensic anthropology that examines taphonomic evidence of marine deposition and shark-feeding activities on human remains (see [11]). The focus remains on the postmortem analysis that can be conducted in the framework of an autopsy done in few hours that follow a fatal attack or the analysis conducted on photographs of the body, once quality images and suitable metrics are available.

2. Shark jaws as potential lethal weapons

Most sharks are predators that feed on other animals they capture, facilitated by adapted jaws holding several lines and rows of teeth. In contrast to mammalian teeth, shark teeth contain fluorapatite, $Ca_5(PO_4)F$, which is harder than hydroxyapatite [12]. Teeth may have different

functions and thus different structures and hardness. For example, teeth of the mako shark *I. oxyrinchus* are curved to the interior and are used to puncture flesh of the prey, while teeth of tiger shark *G. cuvier* have serrated margins and are mainly used for cutting the prey in a sawing motion (**Figure 1**). The serrations vary from one species to another in coarseness and in distribution along tooth edges. Serrated teeth can make greater use of the available biting forces, and they have a greater cutting effect than do smooth-edged teeth (i.e. mako shark *I. oxyrinchus*). The latter depend upon friction which, because the coefficient friction is always less than 1.0 (often very much less), can make use of only a fraction of the total bite force [13]. However, smooth tooth blades can pierce prey with less resistance and are less prone to binding (becoming immobilized) in the prey tissue [12]. In carcharinids (including the bull shark *C. leucas*), heterodonty is characterized by triangular and serrated teeth on the upper jaw aiming at cutting, while teeth from the lower jaw are slender and smoother (see Section 3.4), acting as puncturing/holding devices before the shark starts moving the head laterally for cutting the tissues.
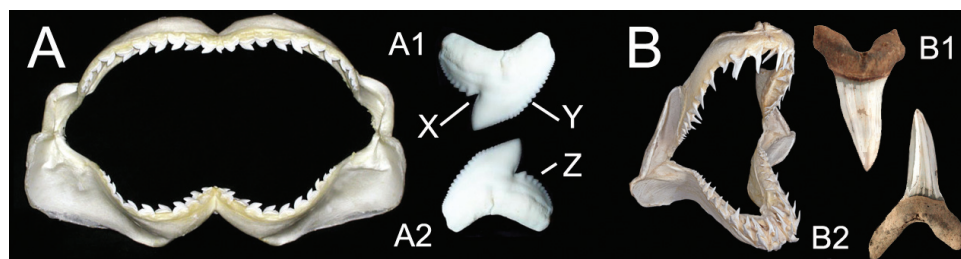
Figure 1. (A) Jaw of a tiger shark, *Galeocerdo cuvier*, showing the specific shape of the upper (A1) and lower (A2) teeth that are similar, showing homodonty between both jaws. The tiger shark tooth displays a strong distal notch (X), as well as fine serrations on mesial sides (Y) and coarse serration on the distal shoulder (Z). (B) Jaw of a mako shark, *Isurus oxyrinchus*, showing curved and thin teeth, smooth-edged without serrations, with a slight heterodonty between both jaws, teeth from the upper jaw (B1) being slightly thicker than those (B2) of the lower jaw (photos courtesy of Simon De Marchi).
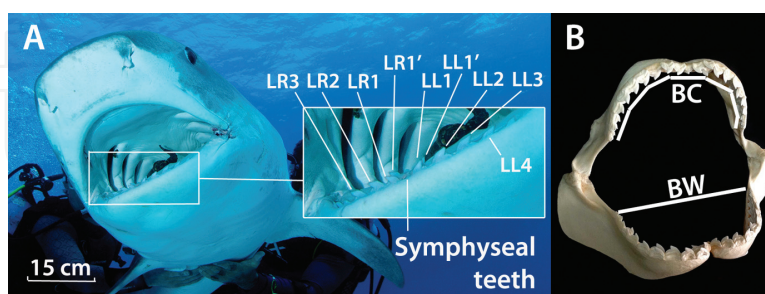
Figure 2. (A) Close-up of central lower jaw of a tiger shark, *Galeocerdo cuvier*, showing the specific shape and position of teeth from the lower jaw. Each tooth is named based on its specific position as follows: First L stands for Lower, second L for left and R for right. LL1, LL2, etc. constitute the first line on the left part of the lower jaw. Note behind LL1 and LR1, the replacement teeth (second row) (LL1' and LR1') that can be responsible for parallel teeth impressions. LL1, LL1', etc. constitute the first row of the left part of the lower jaw. (B) Complete jaw of a tiger shark, *Galeocerdo cuvier* (photo courtesy of Simon De Marchi), that can be characterized by the jaw width, also called 'bite width' (BW), and the jaw circumference, more often named 'bite circumference' (BC). Both measurements can apply for upper and lower jaws, respectively (photos courtesy of Thomas Vignaud, left, and Simon De Marchi, right, for strict scientific use).

Whatever their sharpness and shape, these jaws and teeth constitute a potential threat to humans, also considering that certain species, such as the tiger shark, may produce biting forces of up to 3300 kg/cm^2 [14–16].

The dentitions of sharks are also well known for their ability to regenerate in a continuous conveyor-belt manner throughout life, displaying a high polyphyodontism [17], another characteristic of importance in the context of bite analysis. A tooth series is defined as the active teeth of a longitudinal jaw axis; a row is defined as the in-line teeth of any individual tooth of the active series [18] (**Figure 2**).

3. General features of fatal attacks on humans

3.1. Data for species most involved in fatal attacks

For the 370 shark species described, only 32 were documented as attacking humans, and 3 seem mainly involved in fatal attacks over the world: the great white shark, *C. carcharias*, accounts for around 50% of fatal attacks, the tiger shark *G. cuvier*, for around 20%, and the bull shark, *C. leucas*, for around 18% [1]. These three species are responsible for almost 90% of the fatal attacks, and this general trend is still prevalent. Based on recent outbreaks in Brazil (with 17 fatalities between 1992 and 2005) [19] and La Reunion island (with 9 fatalities between 2011 and 2016), the Bull shark *C. leucas* may pass the tiger shark as the second most dangerous species (**Table 1**). This chapter will focus on the features of these three species as the most probable candidates for documenting a fatal attack on humans.

3.2. The great white shark (*Carcharodon carcharias*)

The large, erect, strong, triangular, serrated teeth of *C. carcharias* allow a fast, high-impact piercing, slicing, cutting and fracturing needed when preying on large marine vertebrates [12] (**Figure 3A** and **B**). Head shape and musculature facilitate rapid lateral head movements in white sharks [20]. Over 70% of attacking white sharks are larger than 10 feet in length [1]. This is a reflection of the shift in dietary preferences of the white shark as it grows [21], moving from fishes to larger prey items such as pinnipeds, cetaceans and potentially humans when the shark approaches 10-feet total length (TL) [22].

White sharks exhibit a typical lamnoid dental pattern, with the upper dentition featuring marked heterodonty with slender teeth in the lower jaw [20, 23]. It is important to note that

Common name	Scientific name	Non-fatal unprovoked	Fatal unprovoked	Total
Great white shark	*Carcharodon carcharias*	234	80	314
Tiger shark	*Galeocerdo cuvier*	80	31	111
Bull shark	*Carcharhinus leucas*	73	27	100
Blue shark	*Prionace glauca*	9	4	13
Oceanic whitetip shark	*C. longimanus*	7	3	10

Table 1. Confirmed species of shark implicated in unprovoked attacks around the world (1580–present) (source: [1]).
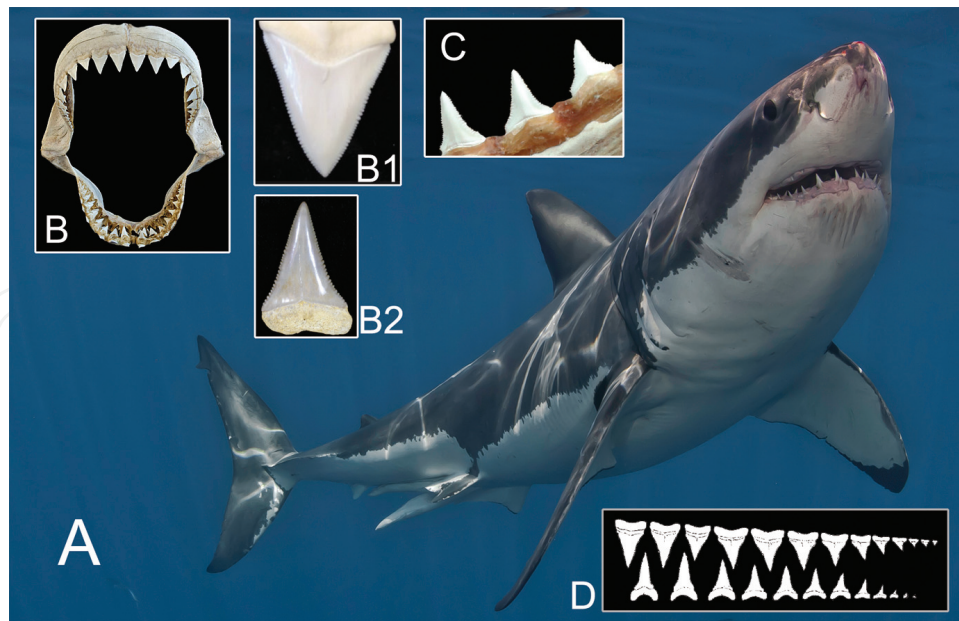
Figure 3. (A) General features of the white shark dentition, showing (B) a sigmoid pattern along a vertical axis of the jaw; anterior teeth are enlarged; anterior, intermediate and lateral teeth are compressed and form a continuous cutting edge; intermediate teeth are enlarged and over two-thirds the height of adjacent anteriors, with reversed cusps that are directed anteromedially. Jaws display a strong heterodonty with (B1) triangular upper teeth and (B2) slender lower teeth, as well as (C) large interdental gaps between teeth from both jaws (here the lower jaw) (photos courtesy of Douglas Seifert and Simon De Marchi for strict scientific use).

white sharks do not have symphyseal teeth [24]. The first and second anterior teeth (UR1 and UR2) of white sharks are erect and nearly symmetrical, while the lateral teeth (UR4 and UR5) become progressively slanted towards the jaw corner [25]. As described by [20], the upper dentition of white sharks features reversed intermediate teeth (UR3 and UL3) (see **Figure 4**). The reversed intermediate teeth (UR3 or UL3) create a significantly larger interspace measurement between it and the first lateral teeth (UR4 or UL4) than between any other two teeth of the upper jaw (**Figure 4**). Generally the large gaps that exist between teeth frequently lead to torn flaps of the skin and flesh between clear-cut punctures. These features should of course be taken into consideration when analysing a bite potentially from a white shark (see Section 4.3).
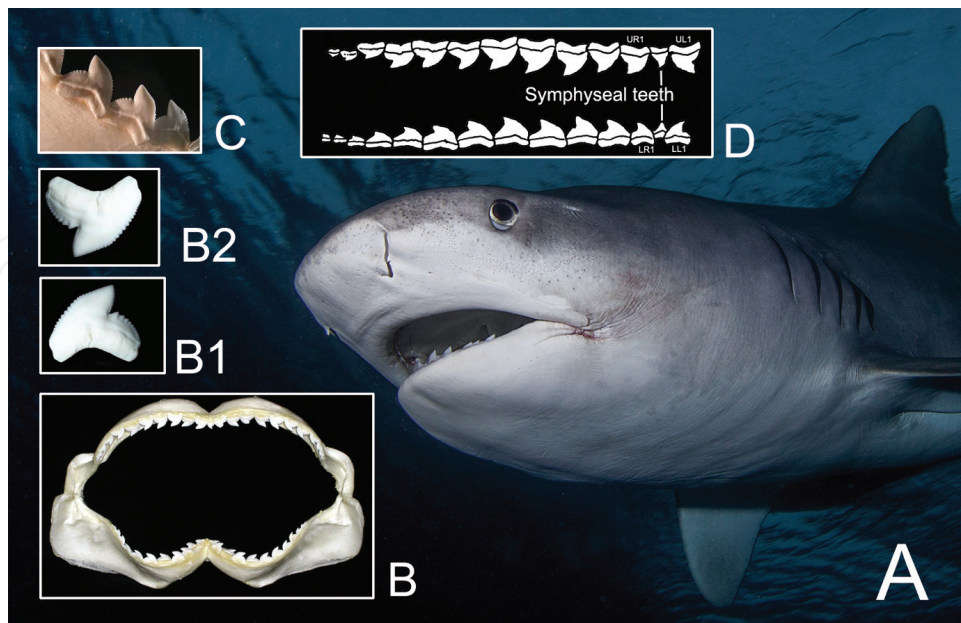
3.3. The tiger shark (*Galeocerdo cuvier*)

Both jaws have large teeth with curved cusps and finely serrated edges. Each tooth has a deep notch on the outer margin lined with numerous cusplets. Upper and lower teeth are similar in shape and size and decrease in size as they move back towards the corners of the mouth. There are 18–24 teeth in each jaw, these teeth forming a single cutting edge (**Figure 5**). The teeth have large cusps, forming a cockscomb shape, with prominent serrations [26]. The strong enamel cusps and serrations help strengthen the tooth structure and dissipate the biting stresses [27]. This makes the tiger shark jaw an extremely efficient and unique cutting tool [28].

The tiger shark is also unique because it has highly kinetic jaws that are exceptionally broad-based, heavily calcified and fused at the symphyses [29]. This allows for the single row of cusped, serrated teeth to extend out from the skull, seize the prey and begin to saw into the bone, performing the 'saw-biting' technique [30]. The broad, heavily calcified jaws, supported
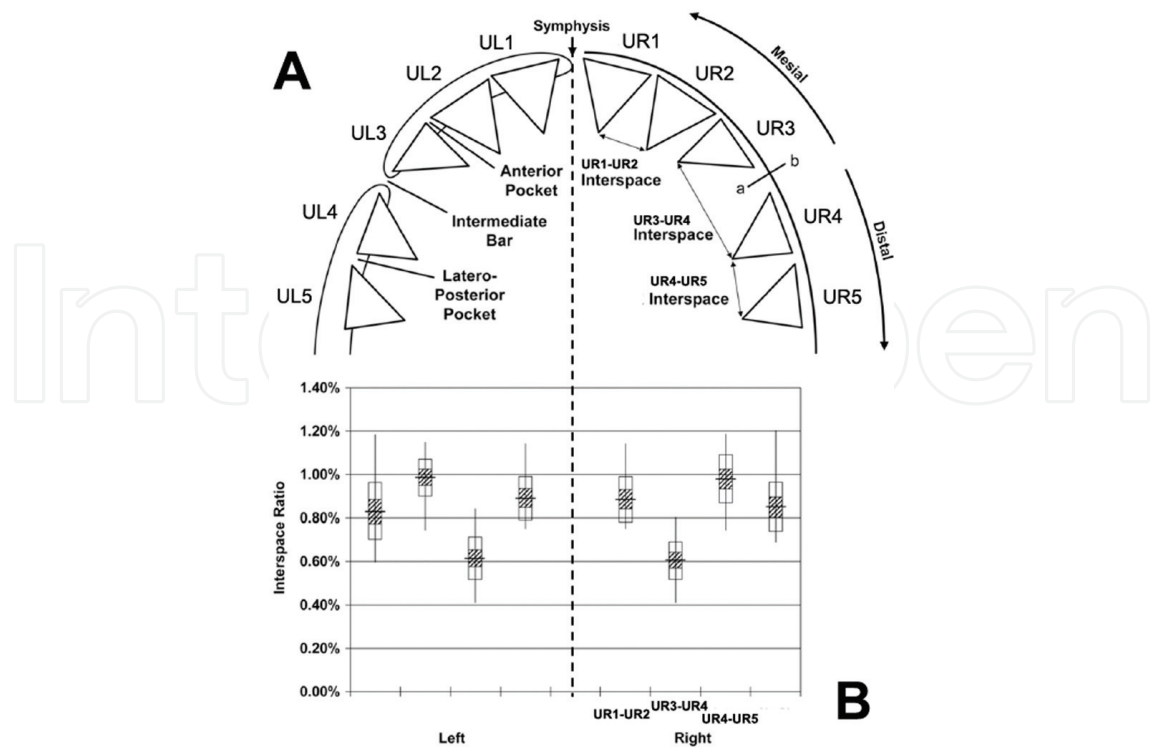
Figure 4. White shark dentition and terminology: (A) jaw terminology, tooth identification and measurements, showing location (indicated by chord a^b) of the intermediate bar between the intermediate (UR3 or UL3) and first lateral (UR4 or UL4) teeth, and (B) dice diagram of interspace ratio between successive pairs of upper teeth, where vertical bar1 = range, horizontal bar1 = mean, white box1 = standard deviation and hashed box1 = 95% confidence limits. In both (A) and (B), the vertical dashed line indicates head axis through the jaw symphysis (adapted from Ref. [20]).


Figure 5. (A) General features of the tiger shark *Galeocerdo cuvier* dentition, showing (B) a sigmoid pattern along a horizontal axis of the jaw; teeth of (B1) the lower jaw and (B2) upper jaw are of similar shape showing homodonty (photos courtesy of Thomas Vignaud and Simon De Marchi for strict scientific use). (C and D) Right side of a typical tiger shark *Galeocerdo cuvier* jaw illustrating the single cutting edge formed by a single row of functional teeth (adapted from Ref. [31]).

by the extra-strong symphyseal fusion, reinforce the entire jaw apparatus and enable the shark to bite through very hard objects such as shells of chelonids [26].

3.4. The bull shark (*Carcharhinus leucas*)

Upper teeth of the bull shark are broad, triangular and strongly serrated, with erect or slightly oblique cusps, and their bases overlap with each other (**Figure 6**); lower teeth have a broad base and are narrow and slender with fine serrations, but no overlap with adjacent teeth bases. Usually, there are 13/12 rows of anteroposterior teeth in each jaw half, but they vary from 12 to 14/12 to 13 [32] (**Figure 6**).

As for many carcharhinids, upper teeth are primarily used to cut and saw (sideways movement along a surface when embedded in it, with ongoing perpendicular pressure); lower teeth are primarily used to puncture and hold prey item in position, with limited capability of cutting and sawing [7].
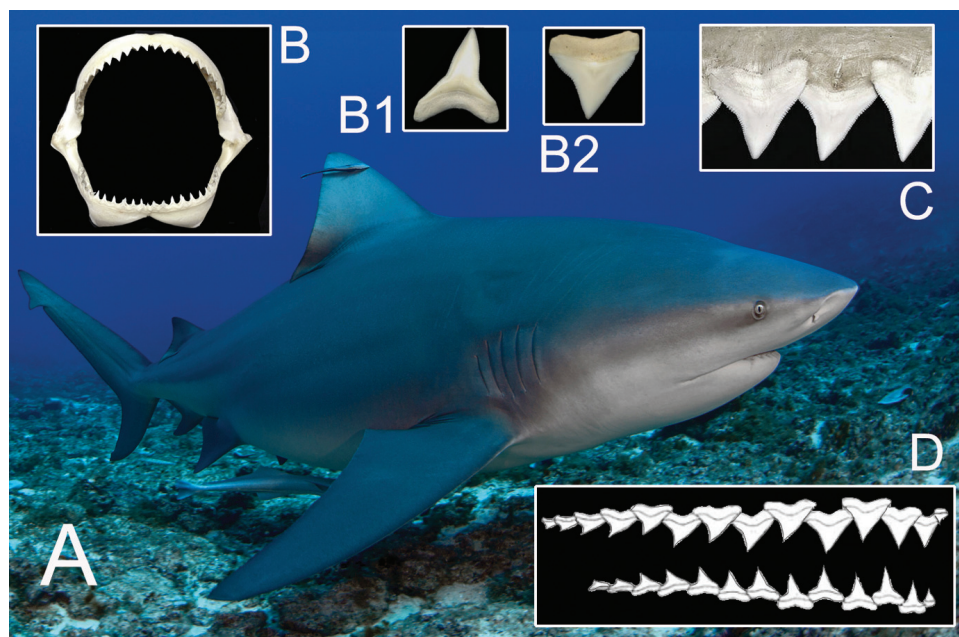
Figure 6. (A) General features of bull shark dentition, showing (B) upper and lower jaws; upper teeth (B2) form a continuous cutting edge with strong overlapping between teeth (C), while lower teeth (B1) are slender, displaying clear heterodonty. (D) Teeth from the upper jaw are usually more numerous than those from the lower jaw (adapted from Ref. [33]) (photos courtesy of Thomas Vignaud and Simon De Marchi for strict scientific use).

4. Post-mortem reconstruction of body length based on wound analysis

Along with the jaw and teeth features of the main candidate species, wound examinations usually focus on the number of bites, margin structure, tooth imprints, wound depth and tissue loss in order to assess the species identity [34, 35]. However, most of the time, these data are insufficient for a reliable identification and must be considered with ecological data about the presence and behaviour of the species (pelagic vs. coastal affinities, seasonality, etc.) and/or, if available, data provided by potential witnesses of the attack.

Historically, the size of the animal was assessed by comparing the length of the individual wound margins with jaws from known-sized animals [7]. Also, regressions that can provide the size of an animal based on the bite width (BW) are available (see **Table 2** for a review of regressions available from the litterature for white and tiger sharks).

However, inspired by studies conducted on cetaceans [39] and based on anatomical differences of jaws and teeth within shark species, Lowry et al. [40] proposed a forensic analysis method of shark bite wound patterns. It is based on the determination of a standard relationship between the measure of the average interdental distance (IDD) and the bite circumference (BC) of the jaw with the individual's total length (TL). The IDD and BC are allometric with the global size and are accurate predictors of the TL of a species-individual. Indeed, one of the numerous elasmobranch characteristics is a continuous replacement of the teeth throughout life, allowing the jaw growth. The number of teeth remains constant, but each new tooth is slightly larger than the one it replaces [41].

Thus, nowadays, in order to estimate length of a shark from an autopsy or file pictures, it might be rapid and reasonable to measure either interdental distances or bite radii from upper or lower jaws, whatever measurements are available, and apply them to established log–log regressions provided by [40] (see **Table 3**).

If the IDD and BC can provide critical information, they might be insufficient for a reliable result. It is therefore necessary to include other measurements of the wounds. Hereafter, we provide a series of case studies that indicate complementary tools that are available in regard to the situation and the available data.

Species	Great white shark *Carcharodon carcharias*		Tiger shark *Galeocerdo cuvier*	
Ref.	[36]	[37]	[38]	[39]
Regression	TL = (BW + 2.4642)/0.0986	BW = 10.4% TL +/− 1.3	BW = 11,7% TL +/− 1.7	BW = 0.12 TL +/− 7.99
n	6 (from 163 to 510 cm TL)	14 M + 19 F (from 170 to 391 cm TL)	10 M + 20 F (from 104 to 410 cm TL)	93

Table 2. Estimated total length (TL) from bite width (BW) for the great white shark and the tiger shark using regressions from the literature.

Type	Jaw	Regression	r^2	p
IDD	Upper	Y = 1.005x−2.111	0.98	<0.001
	Lower	Y = 0.925x−1.808	0.97	<0.001
BC	Upper	Y = 1.007x−0.800	0.98	<0.001
	Lower	Y = 0.966x−0.743	0.99	<0.001

Average interdental distance and bite circumference represent the dependent variables, whereas total length is the independent variable. r^2 = correlation coefficient; *p* = significance level.

Table 3. Log–log regression between average interdental distance (IDD) or bite circumference (BC) and total body length of white sharks, *Carcharodon carcharias*, based on [40].

4.1. The use of the bite width (BW) and bite circumference (BC)

Case study A: description of the wound on a 23-year-old female fatally bitten in a shallow water lagoon in New Caledonia. This case study was adapted from [42–44] *(same case).*

A single large bite was made to the right thigh, from the hip to the knee, with a length of 38 cm (**Figure 7A**). The thigh was cut deeply, with the femur bone broken at the level of the hip. The muscular mass was sectioned but was still attached to the femur bone whose distal part was still articulated to the knee. Despite the large bite, almost no tissue was removed as shown by the repositioning of the scalloped muscular mass on the leg (**Figure 7B**); the inner and outer margins on the wound on the inner part of the thigh fit together well although they are somewhat swollen. The blood vessels were divided, and according to the medical certificate, the victim died from exsanguination and hypovolemic shock. Apart from this large bite on the right thigh, no other wounds were identified on the body.

Given the size of the BC, the hypothesis of the bull shark was rejected to favour either a large white or tiger shark. **Table 4** provides regressions for these two species between the total length of the shark and the width of the mouth/jaw or that of the bite, from the literature. Considering the size of the bite width of 38 cm [44], the total length of the shark would range between 352 and 410 cm TL for a great white shark (for a similar bite width, a tiger shark would be between 250 and 383 cm TL) (**Table 4**).

Using a BC of 596 mm [44] and based on the regressions provided by [40], the species involved in this fatal attack seems to be a great white shark of about 3.5-m TL (**Figure 8**). However, these regressions also show that given a BW of 38 cm, the BC should be much lower than 59.6 cm for the attacker to be a tiger shark for which the TL would range from 250 to 383 cm TL (as shown in **Table 4**). The formula by [40] shows that a tiger shark with a 38-cm BC would have a TL >410 cm (**Figure 8**). This is due to the curvature of the BC which is different between the two species. The hypothesis of the white shark should then prevail. Also, based on behavioural features of the attack (provided by a witness), Clua and Séret [42, 43] concluded that the candidate species for this 2007 attack in Lifou Island was a white shark and not a tiger shark as supported by Tirard et al. [44]. This choice seems to be supported by the tools provided by Lowry et al. [40].

4.2. The use of the interdental distance (IDD)

As demonstrated by [40], the teeth sizes of some shark species vary directly with the total length (TL) of an individual, and a log-linear relationship exists between those two variables. The measure of the IDD can therefore give a reliable estimate of the TL of an individual for most species. The relationship between the BC and length gives a minimal estimate of a shark TL. It is less informative than the IDD because the marks left on the organism or object can be partials, as only a part of the jaw is often used during the bite.

The IDD is measured between adjacent teeth in the first six tooth files (a tooth in the functional row and its replacing teeth are a tooth file) on each side of the symphysis. It is the measure
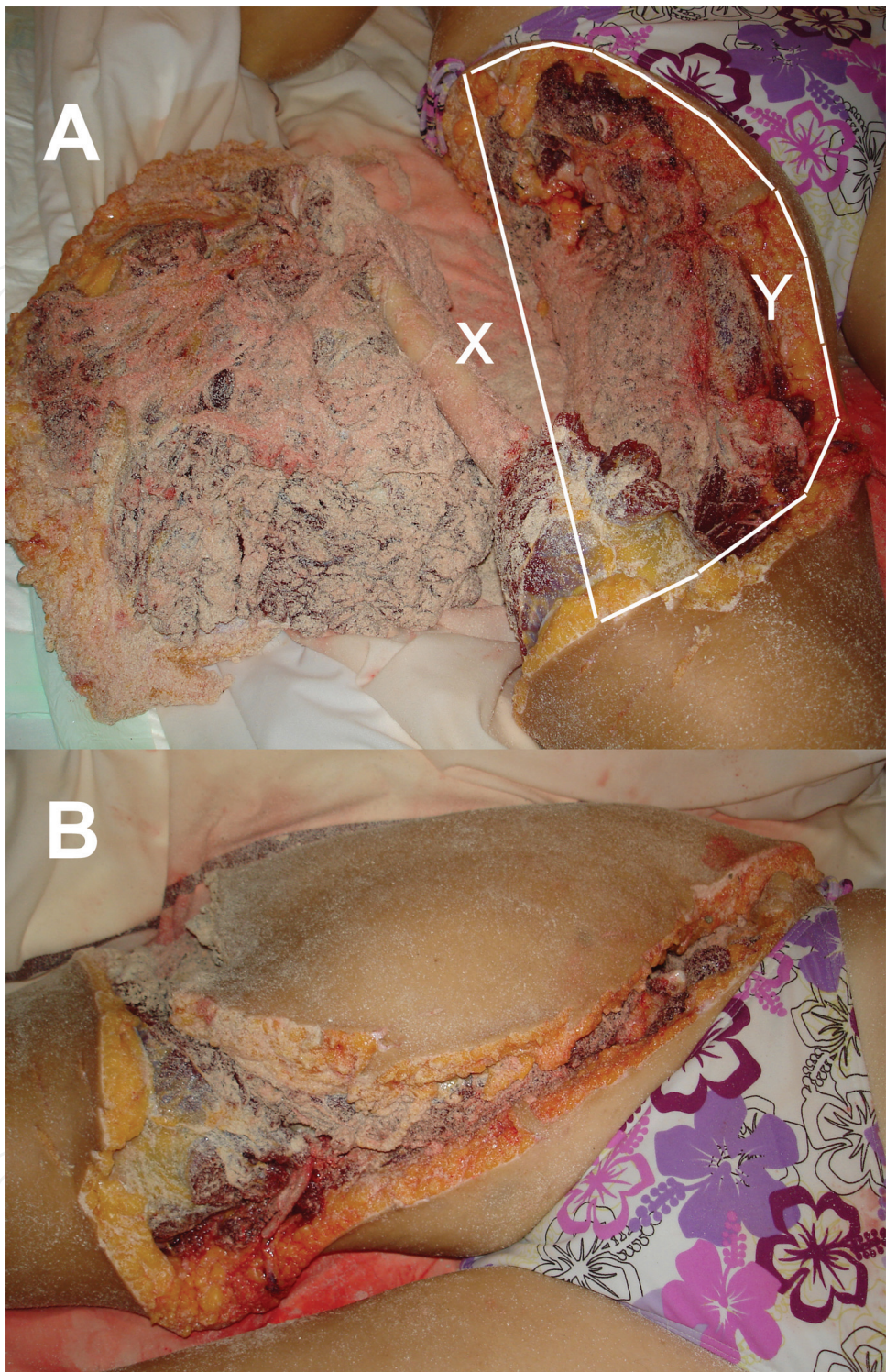
Figure 7. (A) Shark bite on the right thigh of the victim. X shows the bite width (BW) and Y the bite circumference (BC) that were accurately measured on the victim and used for the assessment of the shark size. The bite is not total; the thigh was not removed but is still attached to the knee; the femur is broken at level of hip. (B) The repositioning of the thigh scalloped by the bite shows that there was no significant loss of soft tissue (photos courtesy of Gendarmerie de Lifou for strict scientific use).

Species	Great white shark *Carcharodon carcharias*		Tiger shark *Galeocerdo cuvier*	
Ref.	[36]	[37]	[38]	[39]
Formula	TL = (BW + 2.4642)/0.0986	BW = 10.4% TL +/− 1.3	BW = 11.7% TL +/− 1.7	BW = 0.12 TL +/− 7.99
n	6 (from 163 to 510 cm TL)	14 M + 19 F (from 170 to 391 cm TL)	10 M + 20 F (from 104 to 410 cm TL)	93
BW (cm)	Calculated TL (cm)	Calculated TL (cm)	Calculated TL (cm)	Calculated TL (cm)
38	410.4	352.9–377.9	310.3–339.3	250.1–383.3

Table 4. Estimated total length (TL) from bite width (BW) for the great white shark and the tiger shark using regressions from literature.

Figure 8. Screen copies of the results obtained through the excel table from Ref. [40]. In addition to the scientific paper, [40] provide as a supplementary material an excel table that directly uses the log–log regressions. You must enter either the average IDD or (in this case A) the BC for obtaining the potential species and shark size involved in the bite. NB: the comment 'exceeds TL range regression is based on' does not mean that the species cannot be responsible for the bite, but that the size is larger than the size interval of the sampled animals, indicating potential unreliability of the assessment.

between the tip of a functional tooth and the tip of the functional tooth of the adjacent file (see the interspace between teeth ends from **Figure 4**). The symphyseal teeth are excluded if present; they are often small, misshaped and randomly arranged. The IDD are measured on both sides of each jaw which leads to a total of 20 measurements for each individual [40].

Case study B: description of the wound on a 19-year-old male surfer who was fatally bitten on the outer slope of the barrier reef in New Caledonia (adapted from Ref. [45]*)*

Based on the body examination and the witness' declaration, it was evident that the shark attack was violent and sustained, with several strikes (> 3). Four main wounds could be distinguished: the right thigh was fleshless from the hip to the knee (with exposed femur), the right arm was missing, the right calf showed a large wound with no loss of tissue and a smaller wound was located on the right ankle which displayed clear cuts on medial and lateral sides that had dislocated the joint (**Figure 9**). The autopsy physician determined that death was probably caused by a cardiopulmonary collapse due to the huge haemorrhage on the severing of the axial and femoral blood vessels. To conduct the analysis of the wounds, we mainly used the 'interdental distance' (IDD) and the 'bite circumference' (BC) for assessing the species and size of the shark. Accurate calculation of IDD is actually easier with partial bites, and there was only one photo that could be effectively used for this calculation, showing at the same time a partial bite and a measuring scale (**Figure 9C**).
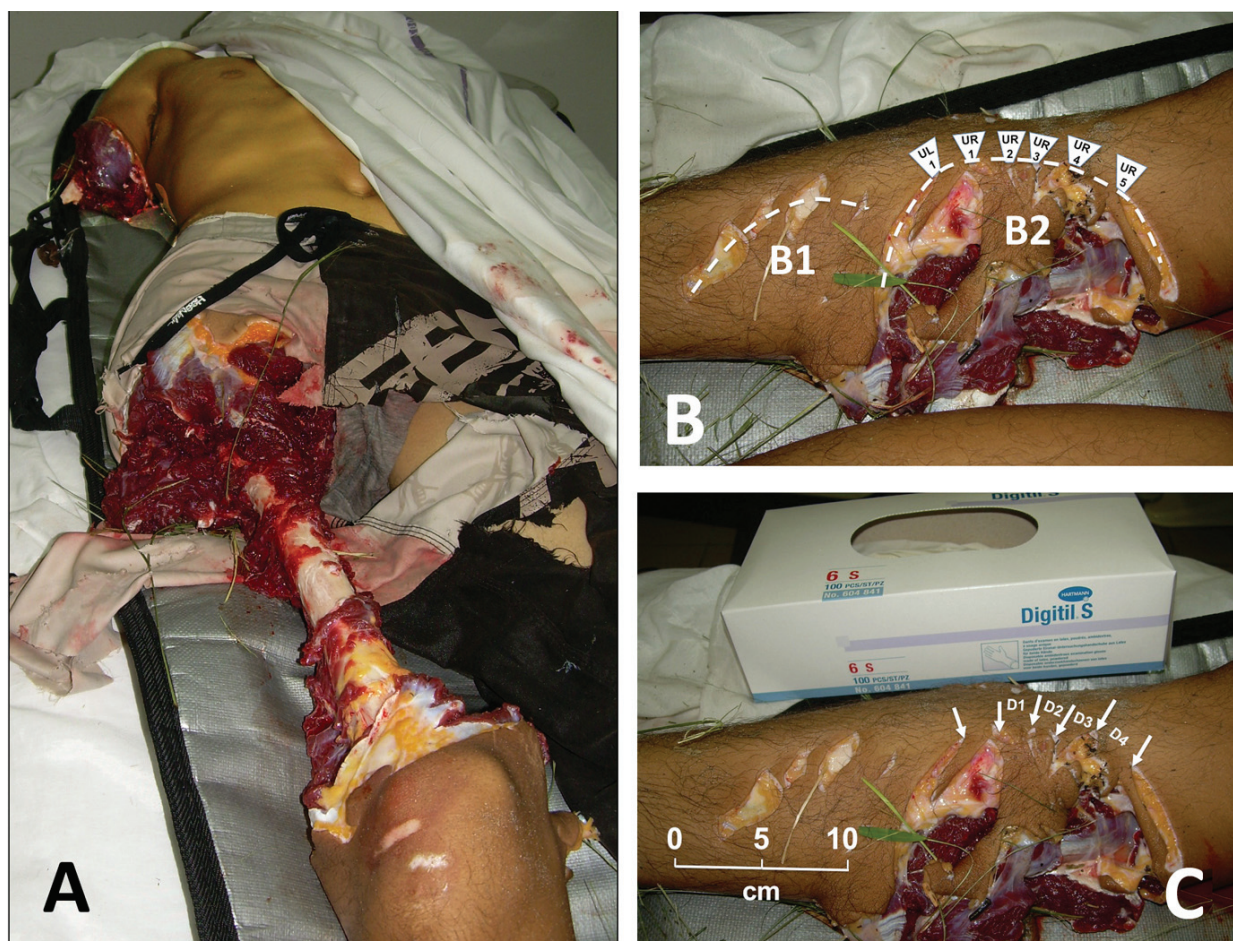
Figure 9. (A) The body of the 19-year-old victim showing the main two wounds in the right arm has been clearly severed 10 cm below the joint of the shoulder (top of the photo); all flesh and muscles have been removed from the right thigh, from the hip down to just above the knee (central and lower part of the photo). (B) Arcs B1 and B2 show the two main bites to the right calf, with tooth impression of the top jaw. For the left-hand arc (B1), it appears that the shark held the leg for a very short time, with a shallow holding bite, and then eased off before biting down and ripping with full force, just below the labelled marks (B2). On B2, we could define the first isolated tooth mark (top left) as the first upper left tooth (UL1), followed then on the right by the upper right teeth (UR1 to UR5). (C) The glove box (24 cm wide) gave us a scale allowing us to calculate bite width as approx. 17 cm, distances between UR1 and UR2 (D1) to be approx. 2.0 cm and UR2–UR3 as (D2) approx. 1.5 cm, UR3–UR4 (D3) approx. 2.4 cm and UR4–UR5 (D4) approx. 2.8 cm. The average IDD for the left bite arc is approximately 3 cm. The bite width probably represents the jaw width at the fifth tooth from the symphysis (photos courtesy of Gendarmerie de Bourail for strict scientific use).

The average IDD calculated on the partial bite of the right calf inflicted by teeth of the upper jaw of the shark (see **Figure 9B**) was 21.75 mm. Based on [40], only two shark species have upper jaw features fitting with such an IDD: a 2.65-total length (TL) white shark, *C. carcharias*, or a 2.25-TL longfin mako, *Isurus paucus*. The occurrence of a longfin mako off the reef barrier on the west coast of New Caledonia has an extremely low probability, as the species has a pelagic distribution. Furthermore, the features of the teeth marks on the body do not fit with elongated, thin and smooth-edged teeth (cf. *Isurus* sp.) but rather with large and serrated teeth with broadly triangular cusps, such as those of a white shark (*Carcharodon* sp.). We therefore

concluded that a juvenile white shark of approximately 2.7-m TL was responsible for this fatal attack.

4.3. The use of other details

Besides the use of IDD and BC for assessing the species and size of the shark, the analysis of the pattern of the teeth marks, directly linked to the species-specific teeth characteristics of the shark, can also be compared with dental impressions of the three main candidate species. Rapid-curing vinyl polysiloxane impression material putty can be used to make these impressions using dried jaws from sharks of accurately measured total length (**Figure 10**). Such a process can help through the identification of specific marks and positioning of the teeth on the wounds, including the shape of tissue and flesh flaps that depend on the teeth position (see Case studies C and D).

Case study C: description of the wounds on a 15-year-old male kite surfer who was fatally bitten in a reef passage of the barrier reef of New Caledonia (adapted from Ref. [47]*)*

On the basis of the body examination and the witnesses' statements, it was evident that the shark approached the victim from below. A major wound (W1, 38 cm in length) with a significant loss of tissue was centred on both sides of the knee in the front and internal sides of the leg. Two other smaller wounds, with almost no loss of tissue, were inflicted on the back of the leg: one at the level of the thigh (W2, 18 cm in length and 10 cm in width) and another behind the knee and the top of the calf (W3, 30 cm in length and 7 cm in width) (**Figure 11**). As mentioned in the autopsy report, the death was undoubtedly caused by a cardiopulmonary collapse due to the huge haemorrhage following the severing of the left femoral blood vessel through the first wound.
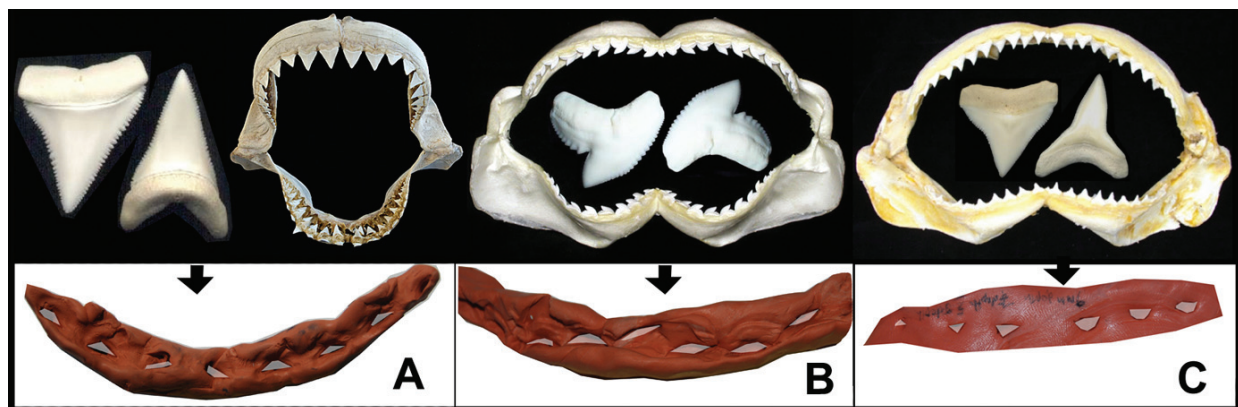

Figure 10. Teeth impressions from the lower jaw of the three main candidate species of shark, potentially involved in a fatal attack (from left to right): (A) white shark, *Carcharodon carcharias*; (B) tiger shark, *Galeocerdo cuvier*; and (C) bull shark, *Carcharhinus leucas*. The teeth impressions of tiger shark are long and thin, very close to each other, sometimes almost overlapping. Teeth impressions of bull shark and white shark are more 'needle-like' and separated, leading to much higher interdental distances (IDD) for a given size of shark. These jaws were collected from the NSW Shark Meshing Program [46] (photos courtesy of Simon De Marchi for strict scientific use).
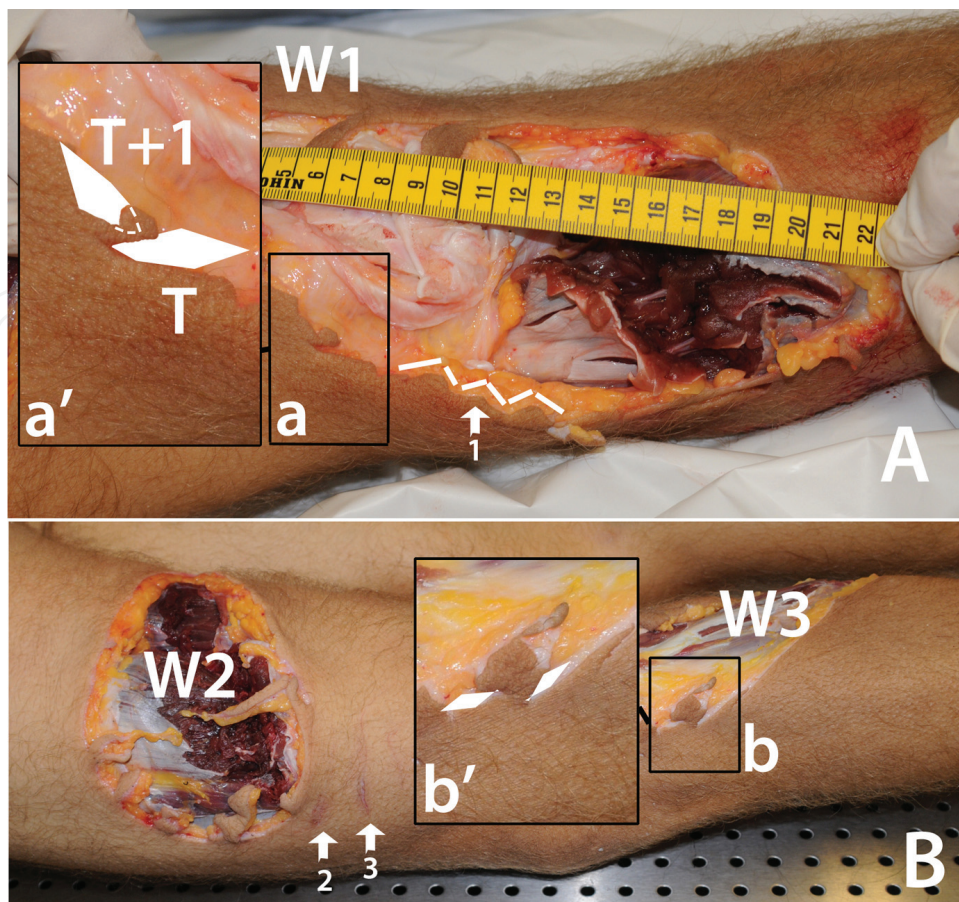
Figure 11. (A) Lateral view of the lower part of the first wound (W1). Arrow 1 shows the specific parts of the wound with sharp and square corners, quasi-parallel cuts, that are characteristic of a tiger shark teeth impression. (a') Close-up view on (a): showing a skin flap which results from two overlapping teeth (T and T + 1). (B) The third wound (W3) has an elongated frame with length 30 cm width 7 cm. (b') Close-up view on (b): showing a skin flap which also results from two overlapping teeth. Arrows 2 and 3 indicate two superficial scratches inflicted by two symphyseal teeth (at the junction of the two jaw segments) (photos courtesy of Gendarmerie de Koumac for strict scientific use).

The analysis of the first wound (W1) revealed that it was probably the result of two different adjacent and overlapping bites or one single bite inflicted as the leg was bending (see [47] for details). Analysis of the lower bite showed that the orientation of the tooth impressions and their shape, together with the small, smoothly sliced flaps, and the very smooth arc of the upper jaw bite, indicate a tiger shark as probably responsible for this attack. This hypothesis was confirmed by the observation of the three teeth impressions from the bottom left of the bite corresponding to this wound. These impressions are more or less parallel and have sharp cut corners, which is consistent with a tiger shark (**Figure 11A**). Also, the shape of the tooth impressions shows no clear morphological differences between those from the upper and lower jaws, indicating dignathic homodont jaws [47], characteristic of the tiger shark, compared to the white shark and bull shark which have dignathic heterodont jaws. In addition to these elements, the shape of some flesh flaps showed that there was an almost overlapping between the teeth (**Figure 11A** and **B**). This detail eliminates the white shark, and regarding the bull shark hypothesis,
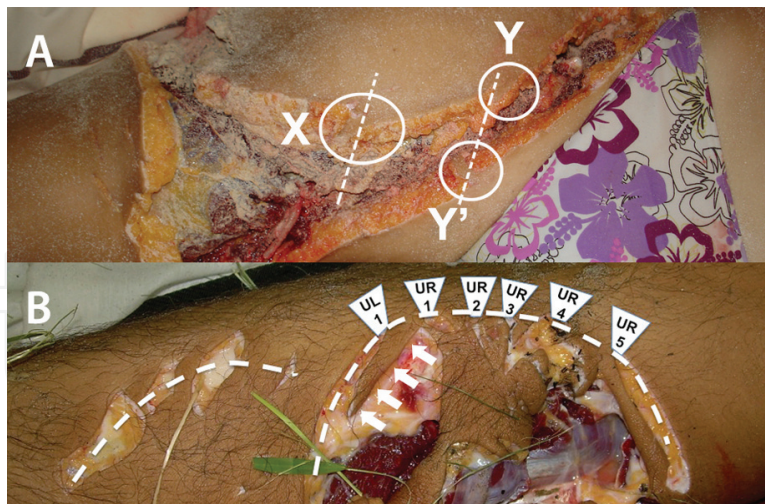
Figure 12. (A) Close-up of the wounds from case A that shows (X) a large flesh flap that seems to correspond to the symphyseal space of a white shark jaw, as well as (Y) and (Y′) flesh flaps that correspond to the large space that exist between UR3/UL3 and UR4/UL4 (see **Figure 4**). The dashed lines indicate the probable biting axis that can explain why both flesh flaps are not exactly opposite each other. (B) Close-up of a partial bite from case B, arrows show a large flesh flap that corresponds to the symphyseal space of a white shark jaw (photos courtesy of Gendarmeries de Lifou and Bourail for strict scientific use).

the overlapping in teeth of the upper jaw is so efficient (see **Figure 6**) that the presence of flesh flaps is unlikely.

Case study D: complementary wounds evidence for shark ID from [42, 45]

Case studies A and B also provide examples of evidence that support the identification of the attacking species. Actually, in both cases, the wounds presented large flesh flaps that are specific to the white shark, given the specific position of its teeth and the large interdental spaces (see **Figures 3** and **4**). In both case studies, it is possible to identify at least a large flesh flap that results from the space between the two first teeth of the upper jaw (UR1 and UL1), combined with the absence of symphyseal teeth (see **Figure 12**).

5. Conclusion

The present research aims at introducing marine biologists and medical practitioners to the basic knowledge necessary for analysing the wounds left by a shark bite. The implementation of these techniques is dependent on directly observing the victim or of the availability of quality photographs. Unfortunately photographic images often do not include any scale measure which significantly lowers the probability of an accurate conclusion.

In practice, these techniques can help but are often insufficient for species identification. It is then necessary to stress the benefit and utility of taking an interdisciplinary approach to forensic anthropological casework, specifically collaborating with a scientist with expertise in shark biology in cases of suspected shark attack. This type of integrated approach is common in taphonomic analyses and should be considered best practice [11].

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