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Identification of shark species based on tooth striation patterns made on bone

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Thesis

IDENTIFICATION OF SHARK SPECIES BASED ON TOOTH STRIATION PATTERNS MADE ON BONE

by

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ABSTRACT

Shark attacks on humans are increasing every year, and due to this fact, it is important to understand the damage that these predators can inflict on bone. The present study examined the striation patterns that shark teeth leave behind on bones during an attack or scavenging event and determined whether they can be used to identify the species of shark involved. The present study examined twelve different species of sharks including white shark (*Carcharodon carcharias*), tiger shark (*Galeocerdo cuvier*), and bull shark *(Carcharhinus leucas*), as there are high incidences of attacks reported of these species. Striations were made in dental wax using the teeth of these species, as well as nine others including blue shark (*Prionace glauca*), tawny nurse shark (*Nebrius ferrugineus*), blacktip reef shark (*Carcharhinus melanopterus*), dusky shark (*Carcharhinus obscurus*), java shark (*Carcharhinus amboinensis*), gray reef shark (*Carcharhinus amblyrhynchos*), sand tiger shark (*Carcharias taurus*), cookiecutter shark (*Isistius brasiliensis*), and lemon shark (*Negaprion brevirostris*), to compare morphologies, their serration patterns, and what striations would be left on bone. It was hypothesized that the striations left in the impressions would be distinct to each species and would provide another method to identify species implicated in attack and scavenging events on humans. The results of this study suggest a statistically significant difference between the patterns of serrations found between some species of sharks

examined. The white shark and the tiger shark can be distinguished from the other species in the present study. Further research on this method should be conducted, so future scientists can identify species involved in predation events and scavenging using striation patterns.

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LIST OF ABBREVIATIONS

ARS…………………………………………………………………Area-restricted search

BC………………………………………………………………...Bitemark circumference

IDD…………………………………………………....................Interdental distance

ISAF……………………………………………………….International Shark Attack File

IUCN……………………………………. International Union for Conservation of Nature

MD…………………………………………………………….…….Mesial-distal width

SMPR………………………………………………. Shark Monitoring Program of Recife

INTRODUCTION

Shark Attack Prevalence

The reported number of shark attacks are on the increase each year, with approximately 139 human-shark interactions reported by the International Shark Attack File (ISAF) in 2020 compared to the 112 reported interactions in 2007 (Chapman and McPhee 2016; Clua and Séret 2010; ISAF 2021). Shark attacks are not a new phenomenon, as the first authenticated shark attack was recorded by way of a painting in 1778 by John Singleton Copley (Bendersky 2002). Shark attacks can be organized into different categories based on the type of attack. An attack is considered to be unprovoked when humans are recreating, such as surfing, diving, or snorkeling, in water where sharks are commonly found (Ballas et al. 2017; Clua and Séret 2010; Clua and Reid 2013; Clua et al. 2014). Unprovoked attacks are the most common, with 57 unprovoked attacks occurring worldwide in 2020, three of which were fatalities. An attack is considered to be provoked when humans are actively trying to draw the attention of sharks. For example, if someone were to be attacked in areas where a fisherman was chumming the waters to attract more fish, or people were cage diving in the hopes of interacting with a shark, either would be a provoked attack (Ballas et al. 2017). There were 39 reported provoked attacks in 2020 worldwide (ISAF 2021). Within the same year, the US had the highest number of unprovoked shark attacks in the world, with 33 attacks occurring on the US coastlines. The attacks in the US cluster around the Florida shorelines, where half of the reported unprovoked occurred, with Hawaii and California coastlines following with five and four attacks, respectively. The other categories to which an attack can be assigned are boat attacks, episodes of scavenging, and attacks that may not be an actual shark attack but rather injuries from a bony fish or stingray (ISAF 2021).

Common Species Implicated in Shark Attacks and their Ecology

The white shark *(Carcharodon carcharias),* tiger shark *(Galeocerdo cuvier),* and bull shark *(Carcharhinus leucas)* are the three species that are credited with the most attacks on humans (Midway et al. 2019). White sharks have the most bites and interactions with humans in Southern Australia, Hawaiian waters are notorious for tiger sharks, and bull sharks hold the record for attacks on humans in the eastern US/Gulf of Mexico region. The International Union for Conservation of Nature (IUCN) Red List has the white shark classified as vulnerable, and the tiger shark and bull shark are labeled as near threatened (Midway et al. 2019).

White Shark (Carcharodon carcharias)

White sharks are one of the few species that are known to attack humans, with their attacks often being fatal (Byard et al. 2006). This is due to their large size; while white sharks often only bite a human once before recognizing that they attacked the wrong prey, those bite wounds create severe trauma that can be fatal (Ritter and Levine 2004). White sharks are the largest species to attack humans, as females, which reach a larger size than males, can grow up to 600 centimeters in length during their lifetime (Bruce 1992, 2008). Their lifespan ranges up to 60 years, although experts believe that range is closer to 40 to 50 years. The white shark has almost no natural predators, orcas

(*Orcinus orca*) being the rare exception, and their mortality is often only estimated. Their reproduction is slow, with estimates of approximately 18 months for gestation and litters of two to 17 pups. The global population of white sharks is also unknown and can only be hypothesized from bycatches from fishermen and tracking information tags that have been released from the individual and recovered (Bruce 2008). The estimate for the current white shark population is approximately 3,500 individuals or less left in the world.

White sharks have a large geographic distribution (Figures 1.1 and 1.2). It was first thought that white sharks were almost entirely a coastal species, spending their time near the coasts of the Pacific and Atlantic Oceans. With recent tagging studies and genetic analyses, scientists have found that white sharks often split their time between the coastal regions and the deep ocean (Bruce 2008). They have been recorded as traveling great distances when tagged; several individuals were recorded on the coast of California in the Pacific and traveled as far as the Hawaiian Islands (Bruce 2008; Casey and Pratt 1985; Long et al. 1996; Martin et al. 2009). They prefer temperate and subtropical waters of all ocean basins and the Mediterranean Sea. White sharks have also been found in some tropical regions, including the Coral Sea, Papua New Guinea, northern Brazil, and the southwest Indian Ocean. In addition, a white shark tagged off South Australia was later captured in New Zealand. There have even been fatal white shark attacks reported near Japan (Ihama et al. 2009; Nakaya 1993). White sharks also respond to season; for example, those that reside on the California coast are found more often at the Farallon Islands in the autumn and move north for the summer, to return to the southern coast in the autumn and winter once again (Bruce 2008; Long et al. 1996). There have been reports of white sharks inhabiting the waters off the coast of California year-round as well (Long et al. 1996).

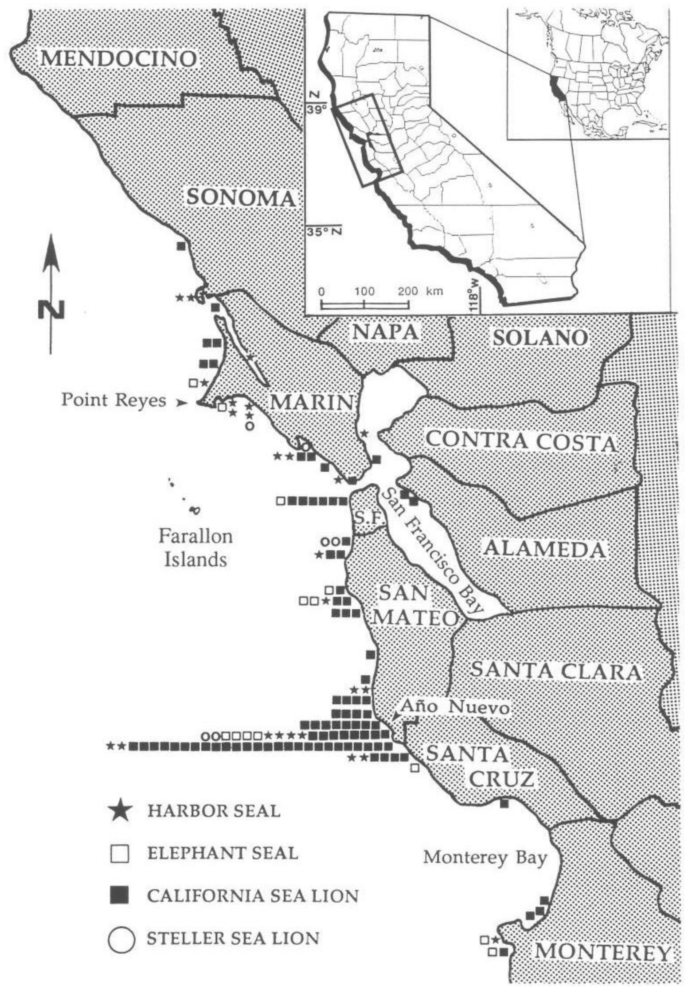


Figure 1.1. California distribution of white shark attacks on pinnipeds (Long et al. 1996:267).

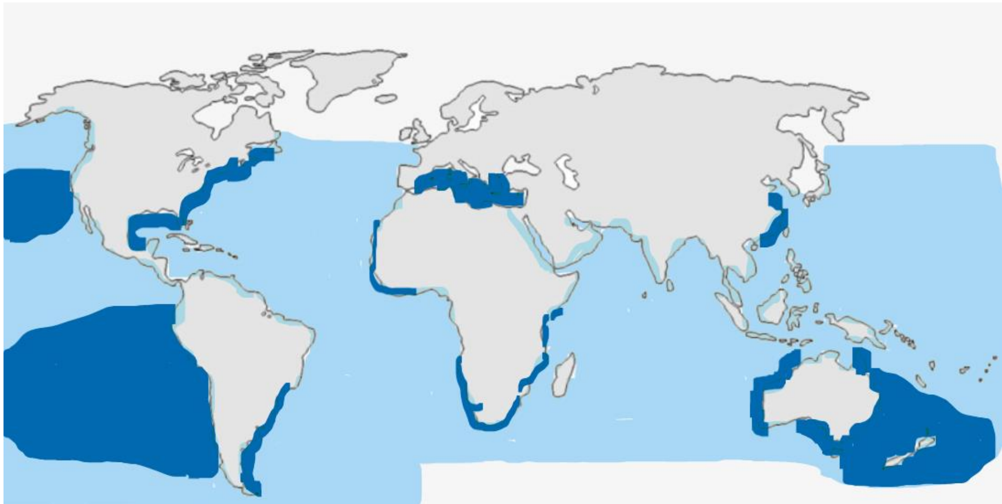


Figure 1.2. Geographic distribution of the white shark, adapted from Ebert et al. (2021).

The diet of the white shark is well documented, as they frequently prey on pinnipeds, as well as various types of fish, sea turtles, cetaceans, and some invertebrates (Bruce 1992, 2008; Casey and Pratt 1985; Heithaus 2001a; Long et al. 1996; Lucas and Stobo 2000; Martin et al. 2009; Towner et al. 2016; Wcisel et al. 2010). Several methods of research, including geographic profiling and tagging individual sharks, have uncovered their many different hunting strategies (Martin et al. 2009). Often white sharks utilize an area-restricted search (ARS), which is described as a sit-and-watch technique, where they stay within a certain contained region or area. They can also employ the active patrolling method, or an active search method in which prey is specifically sought out by the shark (Martin et al. 2009; Towner et al. 2016).

Tiger Shark (Galeocerdo cuvier)

Tiger sharks *(Galeocerdo cuvier)* travel between neritic, or shallower areas that are located above the continental shelves, and oceanic waters (Afonso and Hazin 2015). They are found in nearshore areas and throughout the oceanic basins, which is behavior similar to white sharks, although white sharks are more often found closer to shore. Tiger sharks have large home ranges and frequently travel between those shallower neritic regions and the oceanic basins. They do not have a specific nursery area where they are known to frequent when they pup; however, it is thought that a portion of their population goes to the North Atlantic Ocean to have their offspring in the continental shelf area.

The geographic distribution of tiger sharks (Figure 1.3) is highly seasonal, similar to the white shark; however, they are the most often implicated species in attacks in Hawaiian waters, indicating that this region hosts an abundant population in conjunction with a high level of water sport or recreation activities (Meyer et al. 2018). Due to this reason, several studies of tiger sharks have taken place in Hawaiian waters, as well as tropical regions that host warmer water temperatures, including South Africa and Australia. This allowed individuals to be caught easier or at a higher frequency in areas of warmer water temperatures (Dicken et al. 2017; Heithaus 2001b; Meyer et al. 2014; Meyer et al. 2018). Tiger sharks typically measure between 210 to 440 cm in length, although there have been some individuals that have measured up to 550 cm (Meyer et al. 2014; Meyer et al. 2018).

The diet of the tiger shark is widely variable and includes sea turtles, sea snakes, birds, marine mammals, mollusks, crustaceans, and even anthropogenic food sources

(Heithaus 2001b; Lowe et al 1996; Randall 1992). Some of the anthropogenic consumed items include objects like license plates (Castles 1995; Rathbun and Rathbun 1984). Tiger sharks have ontogenetic shifts in diet; as a pup, tiger sharks consume more fish as well as sea snakes, while a larger shark will add more prey species to its diet, including more marine mammals and sea turtles (Heithaus 2001b). As a tiger shark grows larger in size and begins consuming more food in general as well as larger prey, it can begin to affect population sizes of different species that are more vulnerable to population depletion, like sea turtles and sea mammals. The diet of a tiger shark is also contingent on its geographic distribution. Those that reside in the waters of Hawaii prey more often on teleost fishes, ray-finned fishes that comprise of most ocean species, while those that inhabit the waters around Australia and New Caledonia have a diet dominated by sea snakes. This means that tiger sharks are capable of adapting and can rely on the abundant local species (Afonso and Hazin 2015; Dicken et al. 2017; Heithaus 2001b; Meyer et al. 2018).

Figure 1.3. Geographic distribution of the tiger shark, adapted from Ebert et al. (2021).

Bull Shark (Carcharhinus leucas)

Of all the sharks accused of attacking humans, the bull shark *(Carcharhinus leucas)* is often described as being the most aggressive. A study of bull sharks caught in the southern Gulf of Mexico found that individuals can range from 190 to 250 cm, with females often being larger than males, as seen with white sharks (Cruz-Martínez et al. 2004; Snelson et al. 1984). The bull shark is even more unique, because it is one of the few shark species that can be found in both saltwater and freshwater, leading to a more diverse geographic distribution than many other species (Figure 1.4) (Cruz-Martínez et al. 2004; Ebert et al. 2021). This shark can be found in coastal, estuarine, riverine, and lacustrine waters, preferring to stay near shore. Specifically, they can be found along the continental coasts of tropical and subtropical waters, as well as traveling warm water rivers into freshwater lakes; they prefer brackish waters where saltwater and freshwater meet (Snelson et al. 1984). More pups and juveniles are found in estuaries and river ways, indicating that these are likely the nurseries for bull sharks, and once mature, they will venture into more coastal, nearshore habitats. These areas are also seasonal, similarly to other species, as female bull sharks move into estuaries in spring and summer to give birth before returning to oceanic waters (Snelson et al. 1984).

Unique to the bull shark, and to a lesser extent, the tiger shark, juveniles tend to have relatively larger caudal fins, and the size diminishes in mature adults; it is thought that since mature bull sharks often eat smaller shark species and juvenile bull sharks, that the larger caudal fins are used to enhance the juveniles' locomotion efforts, in order to avoid predation (Irschick and Hammerschlag 2014). This reinforces the belief that bull sharks are aggressive, perhaps the most aggressive shark species, and should be avoided by those recreating in areas where bull sharks can be found.

Figure 1.4. Geographic distribution of the bull shark, adapted from Ebert et al. (2021).

Other Species Included in this Study and their Ecology

Blue Shark (Prionace glauca)

The blue shark *(Prionace glauca)* can be found worldwide in temperate and tropical oceanic waters, with preferred ocean temperatures of 12-20˚C (Ebert et al. 2021). With this geographic distribution (Figure 1.5), the blue shark may be one of the most wide-ranging species of shark. Within this range, they are considered oceanic and pelagic, and can be found past the edge of the continental shelf. As a species, they are highly migratory, and their migrations will often follow major trans-oceanic currents. If the blue shark ventures inshore at all, they usually do so at night around oceanic islands or at the narrowest portion of the continental shelf.

Males and females are similar in length, with males reaching 182-218 cm and females reaching 183-221 cm. Females have litters of around 25-35 pups that are born in the spring or summer following a gestation term of 9-12 months. Females can breed annually or every other year (Ebert et al. 2021). Nursery areas for blue sharks are offshore, with pups remaining in the area until they reach around half of their adult size. Males typically mature faster than females at around 4-6 years, with females maturing around 5-7 years. Blue sharks can live up to 20 years.

The diet for the blue shark generally includes smaller prey such as squid, pelagic fishes, invertebrates, bottom-dwelling fish, small sharks, and the occasional seabird that is taken at the surface.

The blue shark is unique and unfortunate in that it is the most heavily fished shark in the world (Ebert et al. 2021). They are caught for their fins, and it is estimated that the species contributes to 34-64% of the international fin trade. The species’ population is being fished and killed at a rate that they most likely cannot sustain.

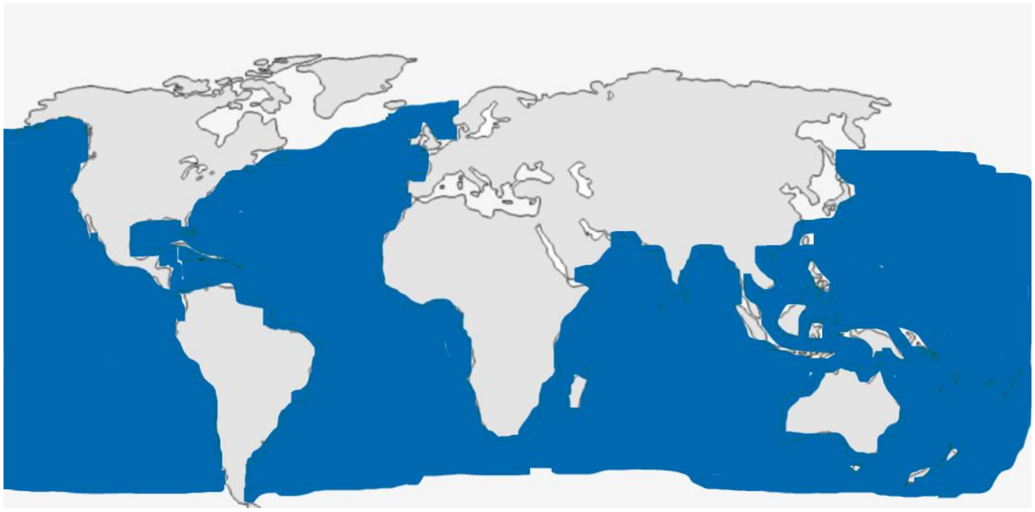


Figure 1.5. Geographic distribution of the blue shark, adapted from Ebert et al. (2021).

Tawny Nurse Shark (Nebrius ferrugineus)

Tawny nurse sharks *(Nebrius ferrugineus)* are located in the tropical Indian Ocean, west and central Pacific Ocean, the Red Sea, and the Persian Gulf (Figure 1.6) (Ebert et al. 2021). Their preferred habitat is on or near the bottom of sheltered areas like lagoons and channels, as well as along the edges of coral and rocky reefs.

The tawny nurse shark is a largely nocturnal species and stalks reefs at night for prey before returning to their daytime resting place, as they typically have a small home range. Males reach a size of about 225 cm in length, and females reach 230 cm. Their reproduction varies with region, with those residing in Australia producing litters of 26 pups, while those in Japan have litters of 1-4 pups. The diet of the tawny nurse shark remains consistent across regions with crustaceans, cephalopods, sea urchins, and reef fishes. In general, this species is docile, and will only bite if consistently harassed.

Figure 1.6. Geographic distribution of the tawny nurse shark, adapted from Ebert et al. (2021).

Blacktip Reef Shark (Carcharhinus melanopterus)

The blacktip reef shark (*Carcharhinus melanopterus*) is located in the West Pacific and Indian Oceans, with some being recorded from the east Mediterranean (Figure 1.7) (Ebert et al. 2021). It is likely that they were introduced to the Mediterranean from the Red Sea via the Suez Canal. They prefer shallow water on coral reefs and reef flats, and they are rarely found offshore or in brackish water.

Males typically measure 90-100 cm in length, with females averaging just slightly longer at 96-112 cm. Females have litters of 3-4 pups after a gestation period of about 8-16 months. The blacktip reef shark is currently experiencing sharp declines in their populations due to unmanaged fishing as a target species, and as bycatch by fisheries, and they are also experiencing habitat deterioration. They are not overly aggressive but have been recorded biting some people swimming or wading on the reefs that they inhabit (Ebert et al. 2021).

A feature that is unique to the blacktip reef shark is that they have differing gastric motility when eating various prey items and by the amount that they have consumed. In this species, gastric acid is continuously secreted, even during periods of fasting. However, digestion can be positively or negatively influenced by the ambient temperature of the water in which the shark inhabits (Papastamatiou et al. 2007). For this reason, digestion is affected by biotic and abiotic factors; it is likely that behavioral and diet strategies are employed due to their environment in order to select the best method to better improve their digestion abilities (Papastamatiou et al. 2007).

Figure 1.7. Geographic distribution of the blacktip reef shark, adapted from Ebert et al. (2021).

Dusky Shark (Carcharhinus obscurus)

The dusky shark (*Carcharhinus obscurus*) can be found worldwide in tropical and warm-temperate shelf waters (Figure 1.8). They tend to inhabit continental and insular shelves, which is a portion of an island that is covered by shallow water, ranging from the shoreline to adjacent oceanic waters (Ebert et al. 2021). The dusky shark as a species avoids estuaries, which differs dramatically from the habits of the bull shark. This species is highly migratory; they move between the subtropical and temperate regions during the summer months and leave as these waters begin to cool in the winter.

Males are the smaller of the two sexes in this species, as they measure around 265-280 cm in length, while females measure 257-310 cm in length, with the maximum length this species measures is 420 cm. Maturity and reproduction vary widely depending on the region; females can have litters that range in size from 2-18 pups, with a gestation period of 16-22 months. Individuals reach maturity around 17-24 years with a maximum age of 53 years. The diet of the dusky shark consists primarily of bony fishes, elasmobranchs (cartilaginous fishes), and crustaceans (Ebert et al. 2021).

Unfortunately, dusky sharks are one of the most vulnerable species to exploitation due to their long reproductive period. They are difficult to protect, because they are often taken by mixed species fisheries. In addition, they have a high mortality rate when taken as bycatch. Dusky sharks are protected in US waters, so the population of juvenile dusky sharks is increasing, but the adult population is still decreasing. These species are also known to be aggressive and have been implicated in attacks on humans (Ebert et al. 2021).

Figure 1.8. Geographic distribution of the dusky shark, adapted from Ebert et al. (2021).

Java Shark (Carcharhinus amboinensis)

The java shark *(Carcharhinus amboinensis)*, also known as the pigeye shark, has a geographic distribution that includes the West Pacific and Indian Ocean, specifically, from South Africa to Australia, and in the East Atlantic (Figure 1.9) (Ebert et al. 2021). Their habitat consists of continental and insular shelves; they are typically inshore near the surf line and along beaches.

Males and females are similar in size, with males ranging from 195-210 cm in length and females from 198-223 cm in length. Females often have litters of 6-13 pups after a 12-month gestation period. The pups are born in the late spring or early summer. The diet of the java shark consists of bottom fishes, crustaceans, and mollusks. They are often misidentified as bull sharks and are less common where bull sharks reside, pointing to possible competition between the two species (Ebert et al. 2021).

Figure 1.9. Geographic distribution of the java shark, adapted from Ebert et al. (2021).

Gray Reef Shark (Carcharhinus amblyrhynchos)

Gray reef sharks (*Carcharhinus amblyrhynchos*) are located in the Indian and Pacific oceans, although they are less commonly found in the east Pacific (Figure 1.10). Like many of the requiem sharks, gray reef sharks are costal-pelagic; they frequent coral reefs and are also found in deeper areas near drop-offs (Ebert et al. 2021). This species is often found in deeper waters than the blacktip reef shark, which often frequents shallow flats. If the blacktip reef shark is absent from these flats, the gray reef shark will occupy this space. Pups of the species also prefer shallower areas, while adults are more likely to inhabit deeper locations.

Gray reef sharks can reach a maximum of 265 cm in length, but they are typically around 130-145 cm for males and 120-142 cm for females. Individuals of this species are considered mature around 6-11 years, but they can live to a maximum of 25 years. Their diet mainly consists of small bony reef fishes, cephalopods, and crustaceans.

At one time, gray reef sharks were one of the most common and abundant species of Indo-Pacific reef shark, along with blacktip reef sharks. However, their population has been severely depleted by unmanaged fisheries, degradation of their habitat, site fidelity, and low reproductivity with litters of 1-6 pups and a gestation of up to 14 months. The gray reef shark can be aggressive, especially when cornered, harassed, or excited by food, so they should be treated with caution.

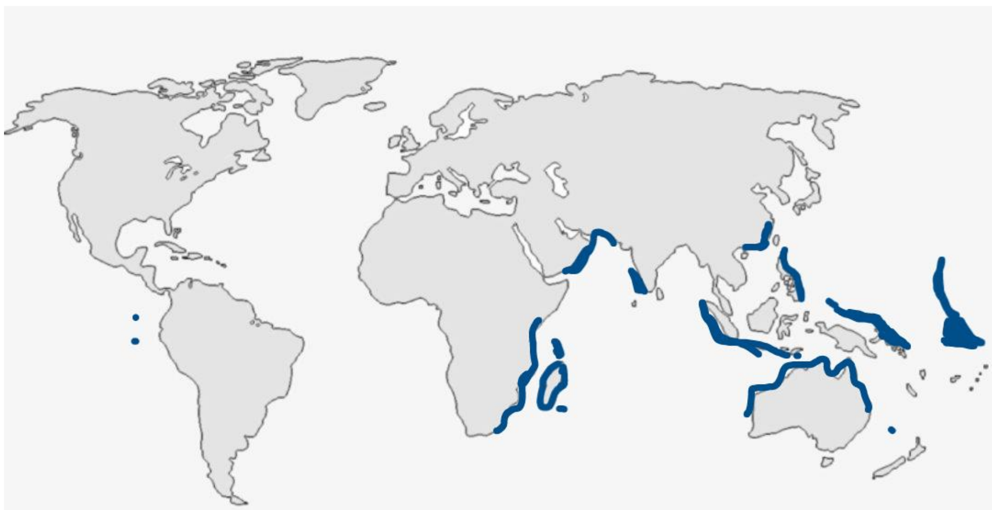


Figure 1.10. Geographic distribution of the gray reef shark, adapted from Ebert et al. (2021).

Sand Tiger Sark (Carcharias taurus)

The sand tiger shark's *(Carcharias taurus)* geographic distribution follows warm-temperate and tropical waters, typically in the Atlantic, Mediterranean, Indian, and west Pacific Oceans (Figure 1.11) (Ebert et al. 2021), Their habitat is that of coastal waters, from the surf zone to offshore reefs. They are also known to inhabit underwater caves, gullies, and reefs. Some populations of sand tiger sharks are highly migratory, but this can vary by region.

Females are the larger of the two in this species, with males measuring around 190-200 cm in length, while females are 220-230 cm in length. Males mature at 6-7 years, while females do not mature until they are 9-10 years. This species is one of the most unique in their mating and pupping strategies. The female will have several developing pups, and during the 9–12-month gestation period, the pups will engage in intrauterine cannibalism, until only one pup survives to be born (Ebert et al. 2021).

The lifespan of the sand tiger shark in the wild is only about 17 years, but they have lived upwards of 30 years when kept in captivity. The diet of the sand tiger shark consists of an array of fishes and invertebrates (Ebert et al. 2021). Unfortunately, many populations of this species are severely depleted and in danger. Because of this, the sand tiger shark was the first legally protected shark in Australia. The species is known for being docile and breeding well in captivity.

Figure 1.11. Geographic distribution of the sand tiger shark, adapted from Ebert et al. (2021).

Cookiecutter Shark (Isistius brasiliensis)

The cookiecutter shark *(Isistius brasiliensis)* can be found throughout the Atlantic, southern Indian, and Pacific oceans as (Figure 1.12). They are a tropical oceanic shark that are wide-ranging and are often found in the bathyal zone, which is the deep sea where the environment is dark and cold. They travel vertically, from the deep sea during the day, to midwater or the surface at night (Ebert et al. 2021).

The cookiecutter is one of the more unique species and one of the smallest in the present study. Males measure around 31-37 cm in length, and the females measure 38-40 cm in length. Females birth around 6-9 pups per litter.

The cookiecutter shark is also known for being ectoparasitic as they are known for attacking prey much larger than themselves by attaching their sharp teeth to the skin of the prey and twist their body around, producing a plug of flesh that is taken from their prey. They have been known to attack cetaceans, pinnipeds, large fishes, and other sharks. They also feed on deep sea fishes, squids, and crustaceans (Ebert et al. 2021).

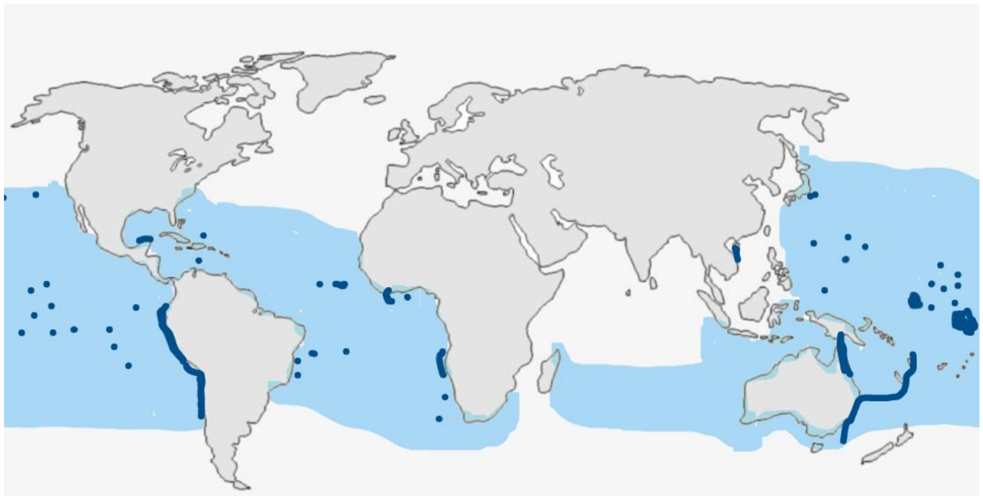


Figure 1.12. Geographic distribution of the cookiecutter shark, adapted from Ebert et al. (2021).

Lemon Shark (Negaprion brevirostris)

Lemon sharks (*Negaprion brevirostris*) are found in the Atlantic Ocean, widespread in the tropical east and west, and in the east Pacific from Mexico to Ecuador (Figure 1.13) (Ebert et al. 2021). This species is inshore and coastal; they usually inhabit the areas around coral keys, mangrove fringes, piers and docks, sand or coral mud, saline creeks, enclosed sounds or bays, and river mouths. The lemon shark is unique in that it has adapted to low-oxygen and shallow-water environments, allowing them to inhabit areas that other shark species may not frequent. Adults may migrate long distances, including to deep water at the start of winter (Ebert et al. 2021).

Males are the smaller of the two in this species, measuring approximately 224 cm in length, while females measured around 239 cm (Ebert et al. 2021). Lemon sharks congregate to mate in shallow water nurseries during the spring months. Females may have litters of anywhere from 4 to 17 pups during the summer after a 10–12-month gestation period. This species is also slow to mature, with individuals reaching maturity at 11-13 years old, and has a maximum lifespan of 30 years (Ebert et al. 2021).

The diet of the lemon shark consists of fishes, crustaceans, and mollusks. The habitat requirements and general disposition of these sharks make them a popular aquarium exhibit.

Figure 1.13. Geographic distribution of the lemon shark, adapted from Ebert et al. (2021).

Scalloped Hammerhead Shark (Sphyrna lewini)

Scalloped hammerhead sharks *(Sphyrna lewini)* have been known to come into contact with humans as well, although more infrequently than the previous three species. Scalloped hammerhead sharks share a number of similarities with the previously discussed species as their geographic distribution includes all oceans and includes the waters surrounding the Hawaiian Islands (Figure 1.14) (Clarke 1971). They prefer tropical and warm-temperate waters. Similarly to the bull shark, the scalloped hammerhead species utilizes estuaries as nurseries, with pups being most abundant in the months of April and October (Clarke 1971). Within a single study conducted by Clarke (1971) in Hawaii, males averaged a total length of 1.9 and 2.7 meters, and though no females were measured, others reported females as being approximately one meter longer than males, following the trend as seen in other species.

Figure 1.14. Geographic distribution of the scalloped hammerhead shark, adapted from Ebert et al. (2021).

Other Aspects of Shark Digestion

Shark species can have specialized digestive systems. In the Caribbean reef shark and shortfin mako shark, individuals have been observed to employ gastric eversion (Brunnschweiler et al. 2005, 2011). Gastric eversion is a way to regurgitate stomach contents. This behavior is often used to remove undigested food particles, parasites, or mucus from the stomach. The retraction of this event is similar to the act of suction feeding (Brunnschweiler et al. 2005, 2011).

The tiger shark exhibits a different unique digestion trait. While they have also been known to exhibit gastric eversion, tiger sharks have been known to halt or slow the rate of their digestion, which allows for retrieval of items from their stomach, up to several weeks after ingestion. This is seen in the famous Australia tattooed arm case, where a tiger shark that was caught and put into captivity was found to have a human arm in its stomach, leading to one of the most infamous murder cases in Sydney (Castles 1995). Other human remains have also been found in the stomachs of tiger sharks (İşcan and McCabe 1995; Rathbun and Rathbun 1984; Stock et al. 2017).

Shark Attack Methods

There are three types of attacks that can occur, each of which can leave different evidence of the attack on the victim and some of the victim's items such as a surfboard or wetsuit. The first type of attack is called a hit-and-run attack. It is the most common type of attack on humans (80%), with most of these occurring in shallow water (Lentz et al. 2010; Stock et al. 2017). This attack occurs when a shark approaches and bites a human once, mistaking the human for their natural prey, and will leave the victim alone after the single encounter. The injuries that humans sustain from these attacks include superficial abrasions from the shark's rough skin and tooth slashes or slight impressions from the shark approaching with an open mouth. These types of injuries are superficial and the least severe of the attack types, resulting in a level one or two on the Shark-Induced Trauma Scale (Lentz et al. 2010). The second type of attack is called the bump-and-bite where a shark will bump into its prey, once to investigate or incapacitate the prey before biting. The third type is the sneak attack where the attack is sudden, there is no warning as with the bump-and-bite. These two attacks differ from the first as these are more likely to take place in deeper water, leading shark biologist to believe that these are more indicative of normal feeding or hunting behavior in which the shark views their human, either correctly or not, as prey. Because these attacks take place in deep water and are reminiscent of feeding behavior, they often involve more than one encounter or bite. These two types of attack are more dangerous and are often deadly (Allaire et al. 2012; Lentz et al. 2010; Stock et al. 2017). This is due to the multiple bites that occur in these two types of attacks, as well as the depth of the damage that occurs, including a significant amount of blood loss, tissue damage, and tissue loss that results in a higher fatality rate.

Characteristics of Attacks by Other Shark Species on Humans

Oceanic Whitetip (Carcharhinus longimanus) *and Shortfin Mako Sharks* (Isurus oxyrinchus)

Other species of shark should be examined, because they do come into contact with humans and are responsible for documented attacks. Levine et al. (2014) examined five cases of unprovoked shark attacks near Sharm-El-Sheikh, Egypt, within a one-week period in 2010, which was a sharp increase from what could be considered the normal rate for shark attacks worldwide, which is 1.4 attacks per week. The species that were likely involved in these attacks were also not the three usual species: white, tiger, or bull shark. Three of the five attacks suffered from a substantial amount of soft tissue being taken from their buttocks, with the three victims also experiencing injuries and loss of tissue of their hand and/or forearms. The shark suspected in these attacks was an oceanic whitetip *(Carcharhinus longimanus)*, and it was likely the same shark in all three encounters. This was because this specific individual was seen during the first two attacks, identified by a unique crescent-shaped notch in its caudal fin. This same shark was also observed on film being fed from a human hand, which was determined to be the motivation behind these attacks; this particular shark was conditioned to associate humans with food. Two other victims were also suspected to be attacked by the same shark, this time a shortfin mako shark (*Isurus oxyrinchus*). A specific individual was identified due to a distinctive jaw injury on its right side. This led to the same irregular and distinctive dental pattern being left in the victim's wounds that were sustained during the attack.

These attacks were likely also caused by an additional outside factor other than conditioning the sharks to anticipate food when they encounter humans. Several days prior to the first attacks, sheep carcasses were dumped within 2 kilometers of the shorelines. While the carcasses were fished from the water, several drifted to the shorelines in the two days leading up to five attacks on the victims (Levine et al. 2014).

Cookiecutter Shark

Cookiecutter sharks are mostly known to scavenge either humans or prey on other living nonhuman species, such as killer whales, different types of large fish, pinnipeds, and even white sharks (Dwyer and Visser 2011; Hoyos-Padilla et al. 2013; Ihama et al. 2009). They leave characteristic scars or wounds on their victims, leading to their common name of the cookiecutter shark, as it looks like a perfectly circular defect. They have also been recorded in many different oceans across the globe, with some recorded attacks near Japan and New Zealand.

Recently, the first recorded case of a cookiecutter shark attacking a living, swimming human, rather than one who was already deceased occurred in Hawaii (Honebrink et al. 2011). A swimmer was crossing the channel between the islands of Hawaii and Maui. Not only was a living person attacked, but the individual was also reportedly bitten twice. As referenced above, being bitten, or engaged by a shark once is a rare occurrence, but twice is exceedingly uncommon. One of the victim's wounds was the characteristic circular, open wound that cookiecutter sharks are known for inflicting. These sharks are known to be active at twilight and during the dark hours of the night, and it is advised that people are aware of the danger that these sharks present if entering the water during these times (Honebrink et al. 2011).

Trauma Characteristics of Shark Attacks

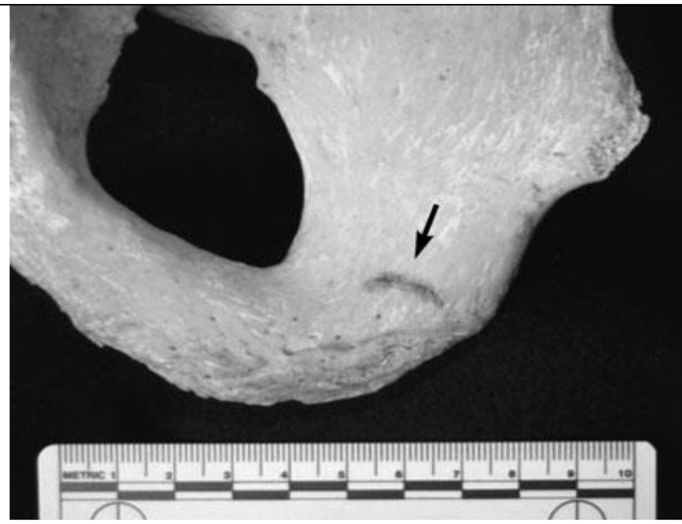
Shark attacks often cause significant trauma to the soft and hard tissues of the human body and often require medical intervention (Allaire et al. 2012; Clua and Séret 2010; Clua and Reid 2013; Clua et al. 2014; İşcan and McCabe 1995; Rathbun and Rathbun 1984; Rtshiladze et al. 2011). Studying the effects of shark attacks or episodes of scavenging on a victim's remains can contribute to understanding how they were attacked and how to prevent damaging or fatal shark-human interactions in the future.

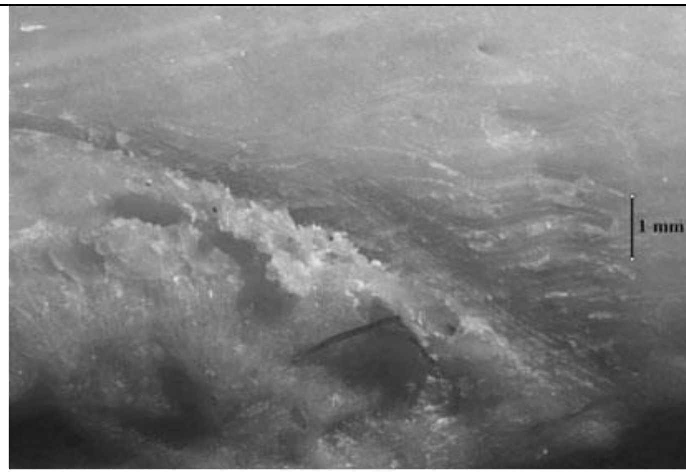
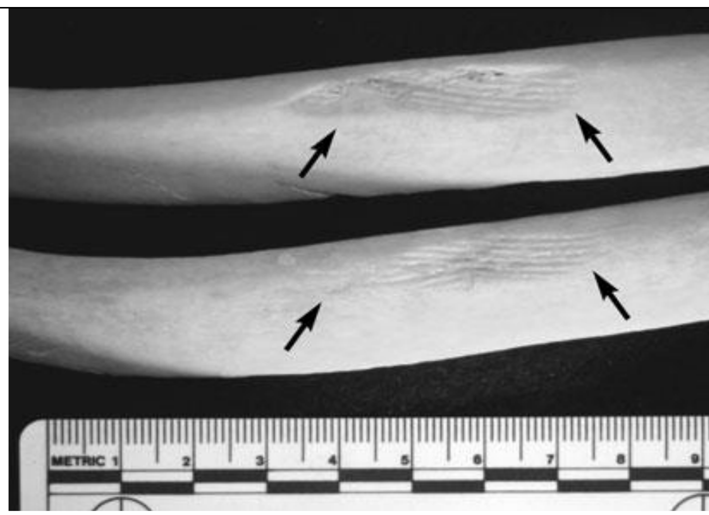
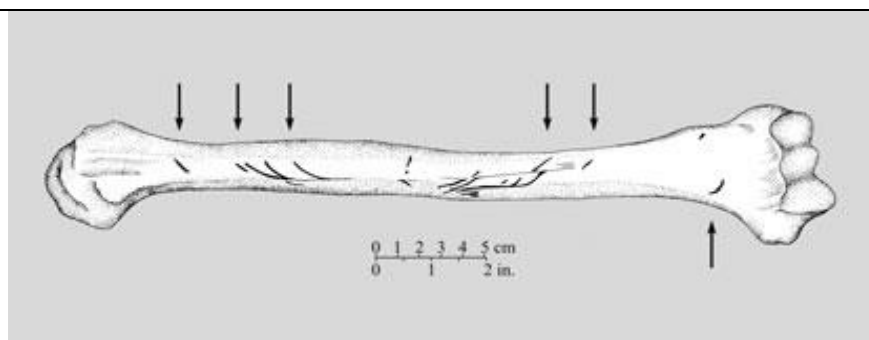
Soft tissue damage that occurs during a shark attack can be extensive and can potentially cause loss of limb or life (Ballas et al. 2017; Bury et al. 2012; Byard et al.

2000; Ihama et al. 2009; Rtshiladze et al. 2011). In the study conducted by Ballas et al. (2017), in attacks at La Réunion Island, soft tissue injuries involving the trunk always resulted in death, and those that had major damage to a vascular structure, found in 11 victims, resulting in death in 55% of individuals studied. In the 13 surviving victims, six individuals required amputations (Ballas et al. 2017). In the two cases presented by Byard et al. (2000), substantial soft tissue injury occurred to a lower limb, severing the femoral arteries, as well as one wrist, resulting in both victims' death from exsanguination. In the deceased, Ihama et al. (2009) described major damage done to the victim's trunks and limbs, resulting in catastrophic damage, especially to the vascular structures of the body, leading to their deaths. The two cases presented by Rtshiladze et al. (2011) that took place in Sydney, Australia, were instances in which both victims survived. Both individuals suffered from severe limb trauma, with both individuals requiring amputation at the level of the wrist.

The severity of bone trauma and the way in which it can occur as a result of a shark attack has been examined previously by Allaire et al. (2012). Those authors created five categories for differing tooth impression morphology and the bone trauma associated (Table 1.1). The first category is a puncture without an associated fracture; this typically occurs with a straight-on bite, specifically when a shark's teeth strike the hard tissue at a perpendicular angle. The second type is a puncture with an associated fracture. This trauma presents when a straight-on bite occurs in the thoracic region, and the characteristic trauma are compression fractures. The third type are striations that occur with bone shaving; in this type, a sharks' tooth enters the body flat at an oblique angle, which causes the serrated edges of a tooth's margin to be marked onto the bone. Overlapping striations are the fourth category of bone trauma that generally occur when a shark's upper and lower jaws move in a sawing motion during a bite event that causes the serrated margins of two adjoining teeth to damage the bone. The last type of bone trauma found are incised bone gouges which often indicate the site of the initial penetration. Soft tissue is generally pulled off during this type of trauma when the teeth slide along bone. If there are multiple gouges and if they are angled in multiple directions, this often indicates more than one bite or attack event (Allaire et al. 2012; Higgs and Pokines 2022; Pokines and Higgs 2015).

Table 1.1. Categories of bone trauma from shark attacks (Allaire et al. 2012:1676-1677).

Type of Trauma	Image
Puncture without associated fractures	
Puncture with associated fractures	

Type of Trauma	**Image**
Striations with bone shaving	
Overlapping striations	
Incised bone gouges	

Shark-Induced Trauma Scale

Table 1.2. Shark-Induced Trauma Scale, adapted from Lentz et al. (2010).

Level of Injury	Total Score	Description
Level 1	0 to 2	Simple lacerations involving the skin and soft tissue, blood pressure unaffected, no loss of function
Level 2	3 to 4	Skin and soft tissue injuries that tend to involve muscle, tendon, or bone; patients are quickly stabilized without much blood loss and function is not compromised
Level 3	5 to 6	Complex lacerations that typically involve muscle, tendon, or bone; patients may have transient hypotension and loss of function of a tendon; likely require future surgical procedures for repair of wounds
Level 4	7 to 8	Aggressive attacks that result in deep tissue damage and loss of function of an extremity or organ; a major vessel is likely to be injured; patients are hypotensive and require immediate surgical intervention to prevent fatality
Level 5	9 to 10 (or F for fatal)	Most likely a fatal injury resulting from the severity of the bite, hypotension, loss of function of an extremity or organ, and rapid blood loss

The Shark-Induced Trauma Scale (Table 1.2) is more often associated with soft tissue wounds than with bone trauma, although bone trauma does factor into how the trauma from an attack is categorized (Lentz et al. 2010). There were five levels developed by Lentz et al. (2010) that have been utilized to describe the features of shark attacks and the types of wounds that determine survivability of an attack. Level one describes simple lacerations to the soft tissue. Level two increases in severity, as muscle or bone damage can occur, but usually no significant blood loss is recorded, and there is no permanent damage caused by the trauma. Level three is described as having complex lacerations that usually involve muscles, tendons, or bones, and the victim often requires additional surgery to repair the damage. Level four approaches a critical level, and the attacks that caused them are labeled as “aggressive”. This is due to the fact that there is deep soft tissue damage and loss of function of either an extremity or major organ. The victims that suffer a level four wound must receive emergency medical care to prevent a fatality. Level five trauma is most likely fatal. In level five attacks, there is usually rapid blood loss and a decrease in blood pressure (hypotension), and it is also likely that there is extensive damage to an extremity or major organ (Lentz et al. 2010).

Studies based on recovered human remains from either shorelines or inside a shark itself can be helpful, as there is often skeletal trauma that occurs, either during an attack in which soft tissue is stripped from the bone of a victim or during a scavenging event, that can provide information on cause and manner of death (Allaire et al. 2012; Anderson et al. 2003; Byard et al 2000; İşcan and McCabe 1995; Rathbun and Rathbun 1984; Stock et al. 2017). Relying on recovered remains has some limitations. The recovery of partial remains does not always provide the investigator with the necessary information to discern the species responsible. There is also a bias that exists when the remains are found inside of a shark, as many make the assumption that the shark that consumed the victim is also the cause of death; however, this is not always the case (İşcan and McCabe 1995; Rathbun and Rathbun 1984).

Challenges with Marine Alteration to Bone

As Pokines and Higgs (2015) found, there are numerous alterations that can be made to bone when exposed to a marine environment. They examined 25 cases of human bones that were recovered on the shoreline or in the ocean waters near Massachusetts, US. Battering/rounding was found to occur in 96% of cases and bleaching occurred in 88% of cases examined. These types of alterations could obscure or completely remove any evidence of a shark attack or feeding encounter, including the effects of scavenging (Pokines and Higgs 2015). Mineral staining, adhering sediments, and adhering taxa can also affect the bone as it is exposed to a marine environment for an extended period. These could also contribute to evidence of any type of shark encounter being erased or otherwise concealed (Higgs and Pokines 2022; Pokines and Higgs 2015).

Other Ways to Identify Species in an Attack

Eyewitness reports of attacks can often provide enough information about the shark involved in the interaction that a probable species responsible can be determined. However, there are times when eyewitness reports become exaggerated and only add confusion or misinformation when trying to make a clear species identification (Tirard et al. 2015). When there are no eyewitnesses and the individual in question is too badly injured or killed, evidence from their remains becomes the main source of information to determine the size and species of animal that could have caused the trauma. This evidence includes shark teeth extracted from wounds, as well as time of year, geographic distribution, and the properties of the wounds sustained by the victim (West 2003).

Metric-based studies on interdental distance (IDD) and bitemark circumference (BC) are important in this regard, because they can be used to estimate the size of the shark based only on the teeth or the marks that teeth leave behind. Teeth can sometimes be found embedded in an attack victim, or the bitemarks are often well-defined on the victims themselves or their clothing and personal affects like surfboard and wetsuits, which allow investigators to calculate IDD and BC (Anderson et al. 2003; Byard et al. 2000; İşcan and McCabe 1995; Lowry et al. 2009; Stock et al. 2017; Tirard et al. 2015). These types of studies can leave certain factors obscured, like the shark behavior that led to an attack or whether the damage was perimortem or postmortem scavenging. There are times where the IDD or BC overlap between species, making the identification of a species not possible (Lowry et al. 2009). A method that has not been utilized thoroughly is the analysis of the teeth striation patterns, as they could lead to a more absolute identification than other methods.

Hypothesis

Taking into account the previous research conducted on shark-induced trauma, it is clear there remains a need to understand what species are responsible for an attack. Currently, if a shark species is suspected in an attack, the overall wound size is examined, with other factors taken into account such as time of year, geographic distribution, and witness account (West 2011). Another method to identify the species involved would be helpful to provide stronger evidence. It is hypothesized that since serration patterns and overall tooth morphology between species may be distinct, the striations left behind will also be distinct between species.

PREVIOUS RESEARCH

The trauma that shark attacks can leave on bone has been documented by several different studies; however, none of these studies directly address whether the striations made by a shark tooth can identify a species (Allaire et al. 2012, Byard et al. 2000; Clua and Séret 2010; Ihama et al. 2009; İşcan and McCabe 1995; Lentz et al. 2010; Rathbun and Rathbun 1984; Stock et al. 2017). Figure 2.1 shows what a striation pattern left by a bull shark could potentially look like on bone (Allaire et al. 2012:1676). The tentative identification of a bull shark was accomplished, not just using the striation presented, but based on other data such as geographic location and bite location, depth, and density. This type of bone damage can occur when a shark bites down on the victim, and its teeth enter at a low, flat angle, allowing the serrated margins of the tooth to scrape the bone as they strip away the soft tissue, leaving an impression of the serrations that are present.

Figure 2.1. Striations on bone presumed to be from a probable bull shark (Allaire et al. 2012:1676).

The following methods are currently the main avenue of identifying a shark species involved in an attack: eyewitness identification of the species by bystanders and the victim themselves, shark trauma identified on remains that are found along shorelines, remains recovered from inside of a shark's digestive tract, and metric analysis of shark teeth and the overall puncture wounds left behind in the victim and the victim's belongings, such as their wetsuit and surfboard.

Eyewitness Identification

Clua and Séret (2010), Clua and Reid (2013), and Clua et al. (2014) are cases where shark identifications heavily relied on eyewitness statements and documentation after an attack, including pictures, police reports, and autopsy reports, but those authors never examined the victims or their bite wounds directly. The authors calculated the IDD and BC from the photographs provided. In the case studied by Clua and Séret (2010), the authors determined that a white shark was behind a fatal attack on Lifou Island in New Caledonia. This conclusion was reached based largely on eyewitness accounts of the attack that attested to behavior more commonly observed in white sharks than any other species. Clua and Reid (2013) examined the photographs of wounds of a fatal shark attack in New Caledonia from which they were able to calculate interdental distance and determined that the attack was by a white shark or a longfin mako. Based on the shark distribution of the area, only a white shark could have perpetrated the attack, because longfin makos are not typically found as far south as New Caledonia. Clua et al (2014) investigated yet another fatal attack in New Caledonia where eyewitness statements and the analysis of IDD and BC conducted from photographs of the wound tracts contributed to the conclusion that this attack was caused by a juvenile tiger shark. The positioning of the wound tracts also indicated feeding behavior of tiger sharks rather than a bump-and-bite attack from a white shark. This is explained by the victim engaging in the activity of kitesurfing, which caused ripples in the water’s surface, similar to that of seabirds. Seabirds are common prey for tiger sharks in this part of their range.

Tirard et al. (2015) re-examined the conclusion reached by Clua and Séret (2010), where the authors had determined that the victim was attacked by a white shark. Upon reexamination of the evidence, Tirard et al. (2015) disagreed, and these authors suspected that a different species was involved. A new examination of the deceased victim in person found that the wounds sustained did not match those of a white shark, but rather of a tiger shark, because white sharks would have caused deep gashes and shredding, which was noticeably absent. Too much consideration for the supposed behavior of the shark from the eyewitness was given, and the fact that the remains were not examined in person may have led to an incorrect identification of the shark species involved in this particular attack. This could be problematic for other studies that based their conclusions on the same parameters.

Remains from Shore Lines

Stock et al. (2017) examined the skeletal indicators of shark feeding on remains; this includes the possibility of a shark attack leading to death as well as probable scavenging activity of sharks on the remains after the individual was already deceased.

The remains from these cases were found off Florida's Atlantic and Gulf coasts. In several of the case studies, there was a shark tooth found embedded in the bones that were washed ashore. However, in these cases only the fact that the teeth were serrated, ruling out species with nonserrated teeth like the mako sharks, was recorded. The remains are no longer available for study, and therefore, the identification of the shark species cannot be determined with any degree of certainty. In a singular case, the defects found on the bones indicated the tooth that created the striations was serrated, once again excluding any species with nonserrated teeth from the list of possible species. As with the previous case, these remains were no longer available to be examined, leaving the identification of the species involved unknown.

Within their research of six separate cases, Stock et al. (2017) highlighted a unique case. This better-documented case consisted of the left and right os coxae and the right proximal femur that were washed ashore from Florida's Atlantic coast (Stock et al. 2017). These remains were determined to be from the same individual due to pair matching, articulation, and similar biological profile indicators, such as an age and sex estimation of a probable adult male. The remains were also identified as being from the same individual due to the same taphonomic history of the bones, and later nuclear DNA identification confirmed that they were from the same individual. Injuries sustained by this individual have a distinct trauma pattern and include torsional loading and sharp-force defects. This injury pattern is consistent with shark predation or scavenging; however, after the individual was identified, it was believed that they suffered a massive deceleration event around the time of death, such as a plane crash, which could also explain some of their injuries. Damage to the remains also consisted of parallel incised gouges along the proximal femur that were the result of a spiral fracture possibly caused by shark feeding activities. Spiral fractures commonly occur when one or more sharks thrash and shake their prey (Stock et al. 2017). Other sharp-force defects on the remains include punctures with and without associated fractures, injuries that are consistent with multiple shark bites (Allaire et al. 2012). All the evidence taken together including the fact that the remains were found off Florida's Atlantic coast, the bone trauma described, the known shark species in the area, and size and pattern of the tooth damage led the authors to conclude that the damage was created by a tiger or a bull shark.

Shark feeding activity, either predation or scavenging, makes it difficult for researchers to determine if the damage was inflicted perimortem or postmortem. While the damage to the bones in the case previously described occurred while they were in a fresh or wet state, the bone damage is likely to be a result of scavenging. This was determined, because the sharp-force defects on these remains and the suite of taphonomic traits indicated a postmortem deposition into the marine environment. Five of six cases in this study were likely to have occurred postmortem. This is supported by the number of sharks that are present in that geographic region, as well as reports from other anthropologists who witnessed bull and tiger sharks scavenging remains in the Gulf of Mexico and off the coast of the Atlantic Ocean (Stock et al. 2017).

Recovery from Inside Sharks

İşcan and McCabe (1995) examined remains found inside of a tiger shark for skeletal trauma that would implicate the tiger shark as the cause of death for the victim. Figure 2.2 illustrates deep gouges on a right proximal femur that were likely caused during the initial bite force of the shark that took the leg. Figure 2.3 is an example of deep gouges on the midshaft of a femur that were also most likely made during the initial attack on the limb. While these marks confirm the attack style and timing, the lack of missing soft tissue, no evidence of crushing or fractures, and the fact that a whole extremity was found inside the tiger shark led to the conclusion that the victim was dead before the tiger shark consumed a portion. Time since death was also difficult to calculate, due to the tiger shark's unique digestive system (Rathbun and Rathbun 1984; Stock et al. 2017). There was little sign of decomposition in this case, so the tiger shark likely encountered the victim not long after death.

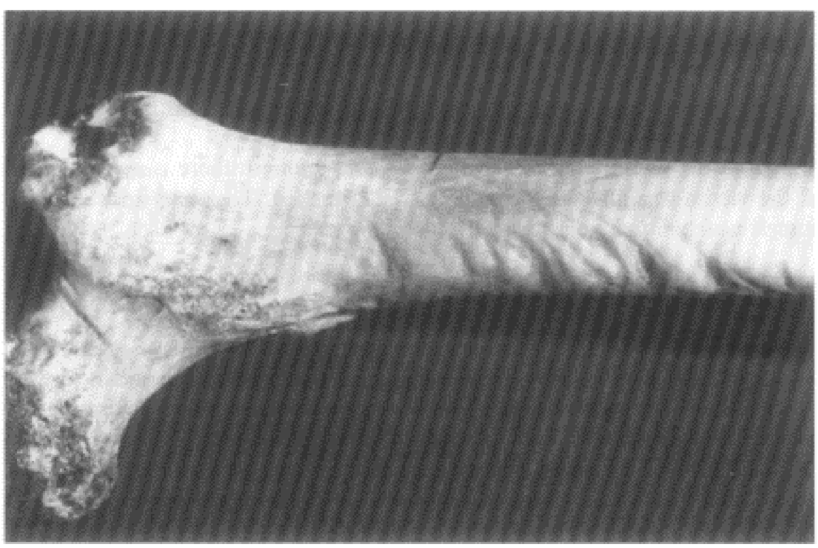


Figure 2.2. Deep gouge marks on proximal femur caused by a tiger shark (İşcan and McCabe 1995:17).

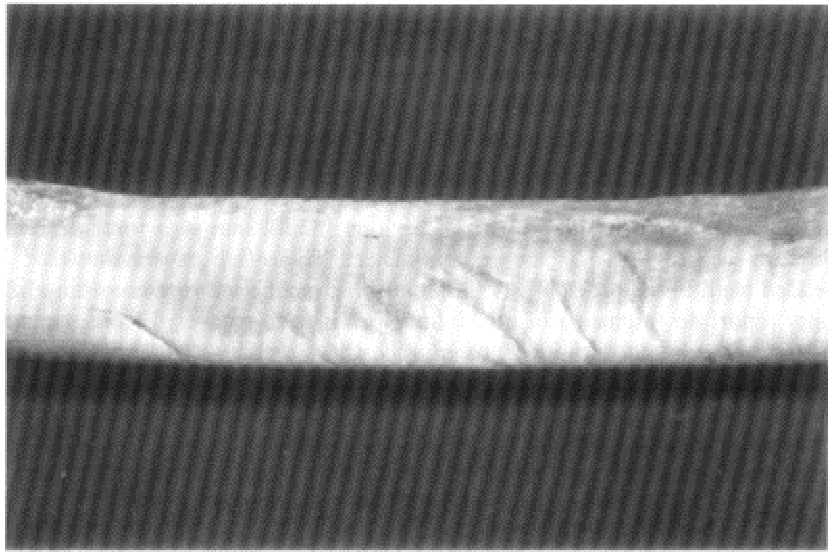


Figure 2.3. Deep gouge marks on midshaft of femur caused by a tiger shark (İşcan and McCabe 1995:18).

Rathbun and Rathbun (1984) also examined human remains found inside of a tiger shark. These authors were able to construct a biological profile of the victim, and they concluded that the remains belonged to a White female, age of 33 years (range of 28 and 38 years), and with a stature estimated to be between 157.5 cm and 165 cm. There was not enough evidence to interpret how the victim came to be ingested by the shark other than perhaps the remains belonged to an individual involved in a plane crash that occurred in the area during the same month that the remains were recovered, but the exact circumstances surrounding the victim's death were ultimately unable to be determined. In both cases, the fact that human remains were found inside of a shark without that animal being the direct cause of death points to a pattern of scavenging behavior that must be considered when examining partial remains with evidence of shark modification (Rathbun and Rathbun 1984).

In addition, those remains that are found inside of the digestive systems of sharks that have been caught could also be damaged from the shark's digestive system, which can lead to any evidence on the bones to be disintegrated by the acidic environment. This includes any damage done to the bone before they were consumed by a shark.

Metric Analyses of Shark Teeth for Identification

Nambiar et al. (1991) focused on white shark teeth, with which they were able to determine a positive correlation between tooth height and overall shark body length. They were also able to quantify that the teeth in upper jaw are 25-30% larger than in the lower. Nambiar et al. (1996) also focused only on white shark teeth in their study. The authors described the different types of peaks that can be observed on any given serrated tooth and quantified how many times a certain type of peak was encountered to determine if a pattern could be discerned. These peak types were small, with the peaks measuring 0.0-1.6 mm wide at its base and 0.0-1.4 mm high, and medium peaks measured 1.6-2.8 mm wide at its base and 1.4-2.0 mm high. There is an intermediate category, the medium-large peak, which the peaks measured 1.6-2.8 mm wide at its base and 2.0-2.6 mm high, just slightly higher than the medium peak. The last main category is the large peak, these peaks measured 2.8-4.0 mm wide at its base and 2.6-4.0 mm high. Peaks could also be categorized as bifid, having two separate peaks, or trifid, having three separate peaks. Figure 2.4 and Table 2.1 show these different categories of peaks. The authors cataloged the different kinds of peaks found on a single tooth and within a single specimen and found that there was not a consistent pattern of serrations within an individual shark. This research was only conducted on three individuals of the same species, so there was nothing that excluded the possibility of identifying the exact species of shark. In fact, they found that they could provide a probable identification of an individual tooth as causing a specific bitemark. However, the patterns of peaks in the serrations, or lack thereof, could not pinpoint the placement of the tooth in the dental arch.

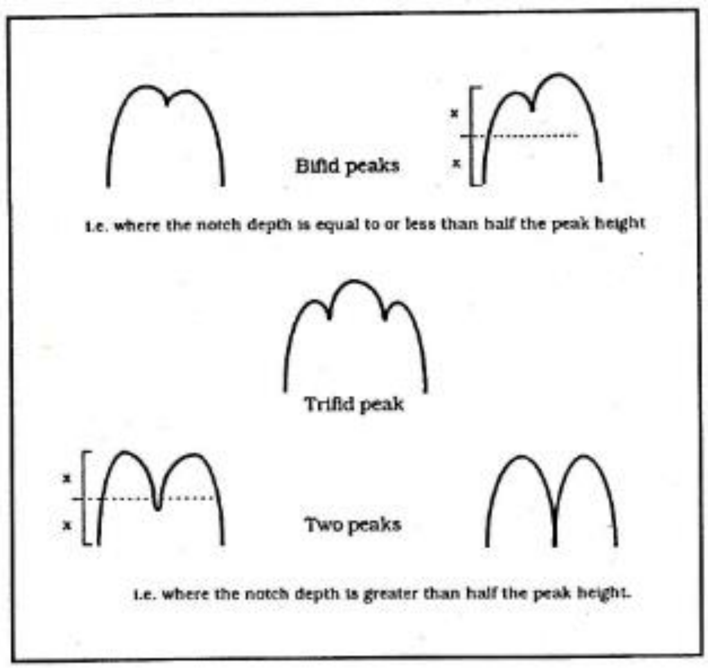


Figure 2.4. Examples of bifid and trifid peaks (Nambiar et al. 1996:4).

Table 2.1. Classification system for tooth peaks (Nambiar et al. 1996:5).

Peak Name	Classification	Description
S	Small peak	0.0-1.6 mm wide at base and 0.0-1.4 mm high
M	Medium peak	1.6-2.8 mm wide at base and 1.4-2.0 mm high
M2	Medium-large peak	1.6-2.8 mm wide at base and 2.0-2.6 mm high
L	Large peak	2.8-4.0 mm wide at base and 2.6-4.0 mm high
B	Bifid peak	2 peaks
T	Trifid peak	3 peaks

Bitemark Circumference and Interdental Distance

Bitemark circumference (BC) and the interdental distance (IDD) allow investigators to infer the size of the individual shark that attacked or scavenged a body (Clua and Reid 2013; Clua et al. 2014; Lowry et al. 2009; Stock et al. 2017). Clua and Reid (2013) and Clua et al. (2014) utilized both IDD and BC based on eyewitness accounts and photographs of the wounds from the victims when determining what species of shark was likely to have caused an attack. Stock et al. (2017) only utilized IDD in one case among their observations, as that is all they could reliably gather from the human remains recovered. Information pertaining to shark size through the examination of BC or IDD can also be obtained by any personal effects that the shark bite, like surfboards and scuba diving gear (Byard et al. 2006). Lowry et al. (2009) took the measurements of IDD and BC from 10 to 24 dry jaws collected from 14 species. These specimens were obtained from both private and public collections, and the specimens were only used if the individual had a verified total length. Lowry et al. (2009) took two average IDD values for each jaw set (one for upper, one for lower) and developed a range for each species. In determining bite circumference, the range was created for upper and lower jaws independently, and it was concluded that the upper jaw BC was larger than the lower jaw in 99% of individuals sampled. Lowry et al. (2009) found that IDD will aid in estimating a shark's total length, while BC can estimate minimum overall length, but BC is often considered to be less precise. While IDD and BC can be helpful in estimating the approximate size of a shark, there is considerable overlap of size between species, which makes identification difficult. The white shark and two mako shark species could be most easily differentiated among those that were included in their study. IDD is more helpful in the elimination of species during an investigation of an attack, rather than identifying the species involved. The most conclusive method for estimating a species involved in an attack without an embedded shark tooth recovered is to use the measurements provided from IDD and BC in conjunction with known geographic distribution, habitat preferences, and shark feeding behavior.

Recovery of Shark Teeth from an Attack

There have also been cases where teeth have been recovered from the wounds of the victims. A non-fatal attack by a tiger shark occurred in the coastal waters of Brazil (Gadig and Sazima 2003). A 25-year-old surfer was attacked and had at least one bite event. A tooth fragment measuring 2.5 mm was removed from the victim's left fibula. A tiger shark was identified as the species at fault given the unique morphology of the species' teeth, with investigators estimating that it came from around the third to fifth position on the upper jaw. The investigators were also able to estimate the total length of the shark from this tooth, indicating that it was likely an individual measuring 2 to 2.5 m (Gadig and Sazima 2003).

Mechanical Properties of Shark Teeth

Enax et al. (2012) examined the mechanical properties of shark teeth, including how the structure and composition influenced those properties, as well as how they differed from the structure and composition of human teeth. They did this by utilizing teeth from two different species of shark, shortfin mako and tiger shark. These two species were chosen specifically, because their teeth have different functions; shortfin mako teeth are better adapted for cleanly tearing prey apart, while tiger shark teeth are better for cutting, or a saw-like motion that rips soft tissue from bone (Enax et al. 2012). Shark teeth are composed of enameloid, which is enamel, dentin, and fluoroapatite; the correlate of fluoroapatite in humans is hydroxyapatite. The authors originally believed that because enameloid is around six times harder than dentine, and that fluoroapatite has a higher stiffness than hydroxyapatite, these factors may have an effect on the function of the teeth themselves (Enax et al. 2012). This study also found that although the shortfin mako shark and the tiger shark teeth perform different functions, they did not differ in their chemical composition. While shark teeth and human teeth have different physical and chemical structures and compositions, it is the morphology of the actual shark teeth that have the greatest difference from human teeth, rather than the chemical structure and composition (Enax et al. 2012). The chemical structure and composition, therefore, must have a different but unknown reason for differing from human teeth, although this could be explained by the millions of years of evolution between sharks and humans.

Whitenack and Motta (2010) examined how three functions of shark teeth (tearing, cutting, and cutting-clutching) performed during puncture and draw test (Figure 2.5). Whitenack and Motta (2010) found that not all prey items were structurally similar, and there were observable differences between puncture and draw among different prey. They found that most teeth from the thirteen species studied were able to perform the puncture and draw tests equally well. They determined that the broader, triangular teeth did not perform at the same level as the narrower teeth, but there was only a slight difference. Because of this, it was observed that most of the tooth morphologies were functionally similar to one another, which led the authors to conclude that shark tooth morphology then does not necessarily lend itself to the direct correlation of biological function (Whitenack and Motta 2010). Combined with the findings of the research from Enax et al. (2012), it can be concluded that even with different morphologies, the functions and composition of different shark species teeth are relatively similar across a breadth of species.

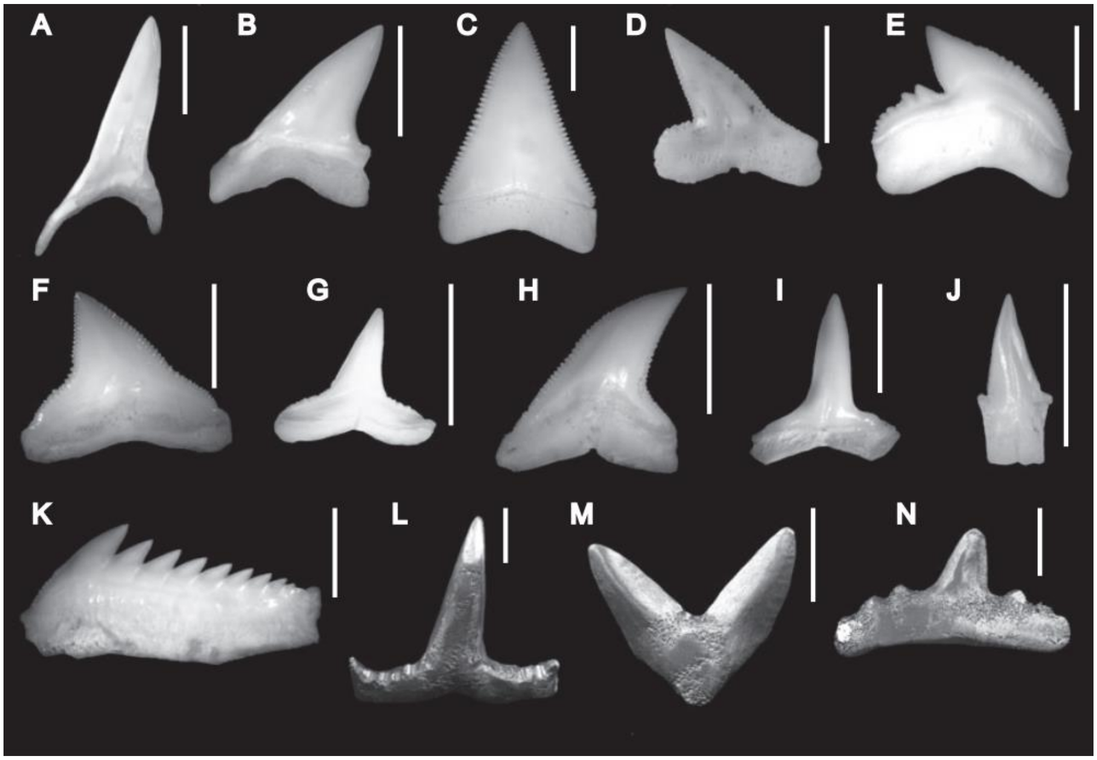


Figure 2.5. Teeth from A. and B. shortfin mako (*Isurus oxyrinchus*), C. white shark (*Carcharodon carcharias*), D. great hammerhead (*Sphyrna mokarran*), E. tiger shark (*Galeocerdo cuvier*), F. bull shark (*Carcharhinus leucas*), G. blacktip shark (*Carcharhinus limbatus*), H. blue shark (*Prionace glauca*), I. lemon shark (*Negaprion brevirostris*), J. knifetooth dogfish (*Scymnodon ringens*), K. sixgill shark (*Hexanchus griseus*), L. aluminum cast of prehistoric (*Cladodous sp.*), M. (aluminum cast of) prehistoric (*Xenacanthus compressus*), N. (aluminum cast of) prehistoric (*Hybodus sp.*) that were used for the puncture and draw testing (Whitenack and Motta 2010:274).

Wroe et al. (2008) examined the bite force mechanics of the white shark and tried to determine how much force white sharks put behind their bites. They utilized a finite element approach as well as computed tomography (CT) scans in order to approach this question of bite force. It was estimated that a 3,324 kg white shark could have a bite force of 9,320 N anteriorly and a bite force of 18,216 N posteriorly; this is the highest bite force of any living creature that has been estimated. For comparison, estimates were produced for the megalodon (*Carcharodon megalodon*), one of the largest sharks to exist, which produced a bite force between 55,522 N and 93,127 N in an anterior bite and between 108,514 N and 182,201 N in a posterior bite.

MATERIALS AND METHODS

Materials

The materials used for this project included dental wax, digital calipers, a photographic scale, camera, measuring tape, and 20 aquarium and museum specimens, utilizing 158 teeth and two full jaw impressions from 12 species of shark; the number of specimens and species are listed in Table 3.1.

As the forensic interest of this project is the striation patterns that can be found on bones, it was important to gather clear striation impressions. As these impressions were captured using museum and dry jaw aquarium specimens, a different medium had to be employed other than bone. Neither of the locations where specimens were borrowed would allow the use of any hard or abrasive medium against their specimens. Dental wax was chosen as the medium, because it was formulated to ensure that the integrity of teeth are not altered while being soft enough to mold to teeth margins and create a clear impression (Kotsiomiti and McCabe 1996). Aside from the fact that the dental wax is softer than bone, it is also more sensitive to temperature. The specific dental wax used came as pink, flat sheets of wax, approximately three by five inches in size, that were pliable enough to be manipulated around the teeth to take the impression, but they were not soft or easily morphed like the clear, gel-like version of dental wax.

Digital calipers were used to take several different measurements, including the height, mesial-distal width, and interdental distance of the teeth. The calipers were also used to measure the height and width of the dental wax impressions of the teeth. The measuring tape was used to measure the bite circumference of both the upper and lower jaws of the specimens.

Specimens

The specimens from which these data were collected are housed in Cambridge, Massachusetts at the Harvard Museum of Comparative Zoology, as well as the Shark Reef Aquarium at the Mandalay Bay Resort and Casino in Las Vegas, Nevada. The present study includes two whole bull shark jaws, two whole tiger shark jaws, two whole white shark jaws, and five individual white shark teeth from different or unidentified individuals. The other species were included in order to present comparative data from common shark species, as well as those that are commonly housed in aquariums, which include one whole jaw specimen from a blue shark, blacktip reef shark, dusky shark, java shark, gray reef shark, sand tiger shark, and lemon shark. In particular, the cookiecutter shark and the tawny nurse shark were chosen from the collection at the Shark Reef Aquarium due to their unique dentition.

Table 3.1. Shark species used in the present study.

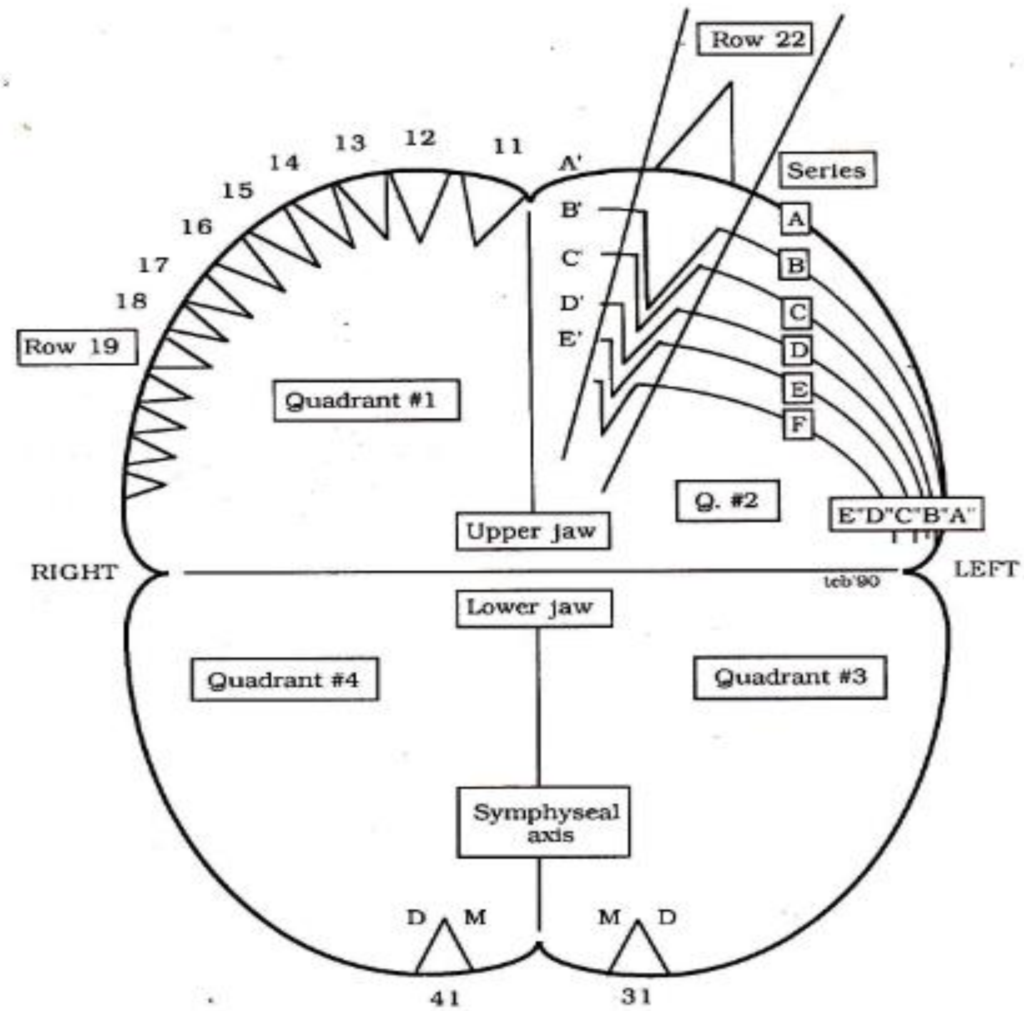
Common Name	Scientific Name	n	Source
White shark	*Carcharodon carcharias*	7	Harvard Museum of Comparative Zoology
Tiger shark	*Galeocerdo cuvier*	2	Harvard Museum of Comparative Zoology and Shark Reef Aquarium
Bull shark	*Carcharhinus leucas*	2	Harvard Museum of Comparative Zoology and Shark Reef Aquarium
Blue shark	*Prionace glauca*	1	Shark Reef Aquarium
Tawny nurse shark	*Nebrius ferrugineus*	1	Shark Reef Aquarium
Blacktip reef shark	*Carcharhinus melanopterus*	1	Shark Reef Aquarium
Dusky shark	*Carcharhinus obscurus*	1	Shark Reef Aquarium
Java shark	*Carcharhinus amboinensis*	1	Shark Reef Aquarium
Gray reef shark	*Carcharhinus amblyrhynchos*	1	Shark Reef Aquarium
Sand tiger shark	*Carcharias taurus*	1	Shark Reef Aquarium
Cookiecutter shark	*Isistius brasiliensis*	1	Shark Reef Aquarium
Lemon shark	*Negaprion brevirostris*	1	Shark Reef Aquarium

Methods

Metric Measurements: Individual Teeth

Methodology and data collection was modeled after Nambiar et al. (1991, 1996). In the present project, data on tooth height and width was collected from specimens, as well as data on the observable patterns in the serrations and the resulting striations of the tooth margins on the dental wax. The compiled data and photographs of these serrations and striations were included to aid investigators in the identification of shark species in the future.

To have the most complete data, dental charting was the first step in collecting data from the dry jaw collections. Figure 3.1 depicts the method followed, with the jaw first separated into four quadrants and each tooth numbered. If a tooth was missing in the dental arcade, that was recorded. The mesial-distal width of each tooth was measured using digital calipers at the base of the tooth, measuring the widest portion from the mesial side, or the side of the tooth that is pointing toward the midline of the jaw, to the distal side, or the side of the tooth that is oriented toward the back of the jaw. The mesial and distal surfaces of the tooth are labeled in Figure 3.1. This measurement is shown in Figure 3.2 as B' to B'. The height of the tooth was also measured using the digital calipers. This measurement was taken by placing one end of the caliper at the base of the tooth, right above the preserved cartilage of the mandible or maxilla, to the apex of the tooth as seen in Figure 3.2 as A' to A". The teeth, whether individual or in a jaw, where the mesial-distal width, height, or impression could not be taken due to extensive antemortem or postmortem damage were omitted from the study. The impressions were still taken, and the measurements of mesial-distal width and height were taken even if the tooth was damaged in some small manner, for example, if the tip was slightly chipped or if there was chipping or breakage on one of the serrated margins. If the tooth that was selected to be used for an impression was damaged or broken in any way, that was recorded in the notes kept during the study.



M = Mesial margin of tooth (the side closest to the symphyseal axis)
D = Distal margin of tooth (the side furthest from the symphyseal axis)

Figure 3.1. Dental charting of a shark jaw (Nambiar et al. 1991:5).

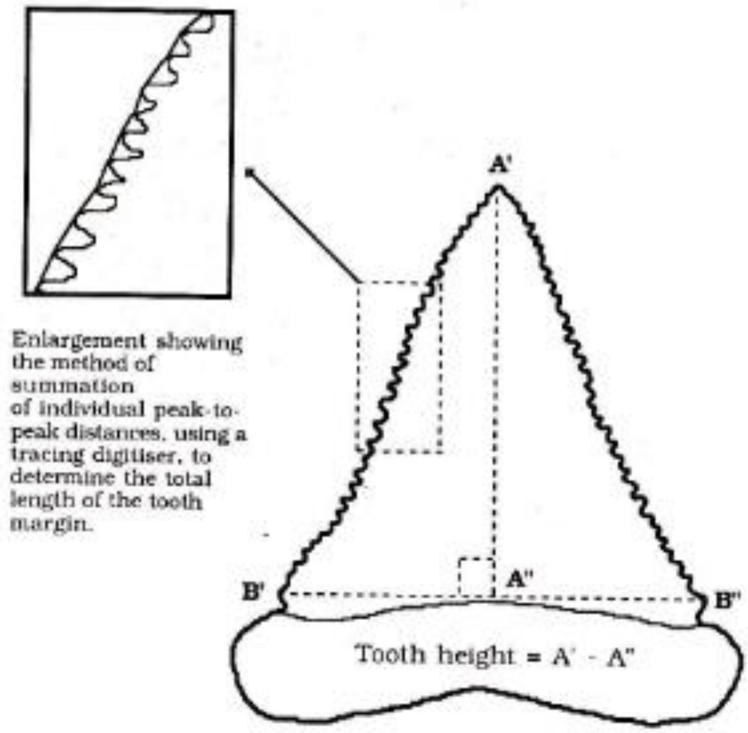


Figure 3.2. Measurements of a white shark tooth (Nambiar et al. 1991:7).

The striation patterns from each tooth of each species were captured by scraping the teeth perpendicularly along their medial and distal surfaces onto dental wax sheets. Adequate mesial and distal tooth serrations were highly dependent on species, tooth morphology, and preservation of the dry jaw. Photographs were taken of the specimens using a digital camera, focusing on the serrations present on the individual teeth, and photographs were taken of the whole dry jaw of the individual. The striations made in the wax were also photographed with the digital camera for comparison to other species, as well as to capture the impression in case the wax was compromised at a later date.

Metric Measurements: IDD and BC

Following the procedures of Lowry et al. (2009) (shown as the short line in Figure 3.3), the interdental distance (IDD) of the six most anterior teeth within each quadrant on both the lower and upper jaws of the whole dry jaw individuals was taken. This was accomplished by using a digital caliper; the digital caliper was positioned at the apex, or the tip, of one tooth and measured to the apex of the adjacent tooth to determine the distance between teeth. For individuals where there was only one tooth missing of the six most anterior teeth, especially if the teeth were the most distally located, that measurement was included due to the small sample size. For individuals that were missing more than two of the six teeth needed for an accurate IDD measurement, especially if the teeth missing were adjacent, the IDD was not measured due to insufficient data. Also following Lowry et al. (2009), the bitemark circumference (BC) was measured for the whole dry jaw individuals. This was accomplished with a measuring tape and measuring from the most posterior, or distal tooth, on one side of the lower or upper jaw, across all the teeth to the most posterior, or distal tooth, on the other side (Figure 3.3). The measurements for both the upper and lower jaws were collected separately and recorded. If the dry jaw was compromised by excessive warping during the preservation process, that was noted, and the measurement was taken but excluded from statistical analysis.

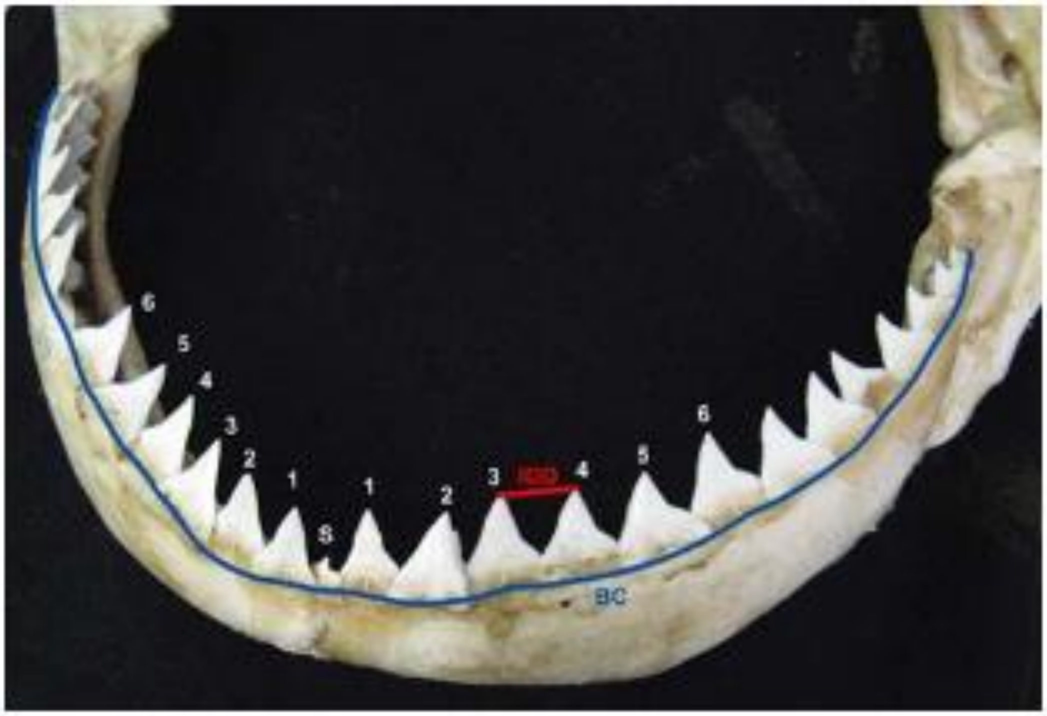


Figure 3.3. A bull shark lower jaw with interdental distance (IDD) (short line) and bite circumference (BC) (long line) depicted (Lowry et al. 2009:2486).

Impressions

Adapting the categorization method from Nambiar et al. (1996), the individual teeth and their corresponding impressions were categorized into eight different groups based on their striation pattern. Nambiar et al. (1996) focused on classifying individual peaks of a tooth’s serrations, whereas the present study aimed to classify the overall striation pattern left by the serrations. The small, medium, and large peak categories were used from Nambiar et al. (1996) (Table 2.1) and an additional qualification was added. This qualification examined the uniformity of the serration and resulting striation pattern, If the striation pattern recorded was uniform in pattern, meaning that the striations in the wax recorded the serrations present on a physical tooth and those peaks were evenly formed and spaced, these striations were considered uniform. If the striation was interrupted, indicating that the serrations or peaks were not recorded in the striation impression, or if the peaks were unequal in size, then the pattern of serrations was considered not uniform in pattern. These qualifications of uniform or interrupted patterns prompted subcategories alongside mamelon, or the individual peak, size. The new classifications are listed in Table 3.2. For example, if the tooth was non-serrated, then they were classified as a 0. The 0.5 classification was described as the tooth itself being non-serrated with a slight pattern in the impression, but they were too small to be measured. A classification of 1 indicated that the average mamelon size was small, 0.0-0.4 mm, and the striation pattern was uniform (i.e., the spacing between serrations was equal). A classification of 1.5 indicated that average mamelon size was small, 0.0-0.4 mm, but the striation pattern was interrupted (i.e., the spacing between serrations was unequal). Following in the same pattern, the striations that were classified as a 2 had an average medium mamelon size, 0.04-0.9 mm, with a uniform striation pattern, and a 2.5 classification had an average medium mamelon size with an interrupted striation pattern. A classification of 3 meant that the tooth averaged a large mamelon size, 0.9-1.4 mm, with a uniform striation pattern, and a 3.5 classification averaged a large mamelon size with an interrupted striation pattern. The numbers were scaled back from Nambiar et al. (1996), because those researchers were working with white sharks, who have the largest teeth and serrations of any extant species, and their classification started at 1.4 mm.

Table 3.2. Adapted classifications of peak patterns from Nambiar et al. (1996).

Category Name	Classification	Description
0	Non-serrated (no mamelons)	Impression is smooth
0.5	Non-serrated with distinct impression pattern	Impression is smooth with a slight pattern; peaks cannot be measured
1	Small mamelons w/ uniform pattern	0.0-0.4 mm mamelon size with a uniform striation impression
1.5	Small mamelons w/ interrupted pattern	0.0-0.4 mm mamelon size with an interrupted striation impression
2	Medium mamelons w/ uniform pattern	0.4-0.9 mm mamelon size with a uniform striation impression
2.5	Medium mamelons w/ interrupted pattern	0.4-0.9 mm mamelon size with an interrupted striation impression
3	Large mamelons w/ uniform pattern	0.9-1.4 mm mamelon size with a uniform striation impression
3.5	Large mamelons w/ interrupted pattern	0.9-1.4 mm mamelon size with an interrupted striation impression

The height of the striation impressions was also measured using the digital calipers. These measurements were analyzed in conjunction with the tooth measurements and the classification of striations patterns to quantify the distinction between each species.

The impressions from the Shark Reef Aquarium were taken in August 2021, which is the height of summer in Las Vegas. Precautions were taken to ensure that the impressions were captured by photograph directly after they were taken in the event that the wax became corrupted in any way by the heat.

Photographic Data

An additional goal of the present study, other than to identify shark species based on their striation patterns, is to present photographic data that can be used by researchers and investigators in the future when identifying the shark species involved in an attack. The data gathered by the methods above, as well as photographs of the different species' teeth and the corresponding striation patterns that were collected have been codified. Future researchers who examine shark striations left on bone or other material can use these enhanced photographs of the individual species' serration and striation patterns as a supplement to the other research that has been conducted. The striation patterns pictured could be used to narrow down potential species.

Statistical Analysis

With the various measurements taken and the impressions put into one of eight categories, Kruskal-Wallis analyses were conducted to determine if there are any significant differences in the patterns of the striations, and if these differ from species to species or if there is a species-specific pattern to the serrations in the striations themselves. The height and width of the different species' teeth was also analyzed and plotted in order to understand the relationship between the average overall tooth size and striation size, in an effort to determine species from striation patterns.

RESULTS

Tooth Measurements

Height and Mesial-Distal Width

The average mesial-distal width and height was calculated among 11 of the 12 species studied and is shown in Table 4.1. The tawny nurse shark had small and practically immeasurable teeth, and any resulting measurements would not be accurate. The dusky shark (*Carcharhinus obscurus*) has the smallest teeth of the large-bodied species, in both width and height; however, the cookiecutter shark had the overall smallest measured teeth, with an average MD width of 2.95 mm and average height of 6.35 mm. The white shark has the largest teeth on average, in both width (22.96 mm) and height (22.23 mm), although the sand tiger shark almost matched the white shark's average height. The sand tiger shark, however, has narrow nonserrated teeth, which distinguishes them from white shark teeth. The three top species that attack humans (white, tiger, and bull sharks) all have differing averages that are not close to any other species recorded here. The blue shark (*Prionace glauca*) and the sand tiger shark (*Carcharias taurus*) are the two species that are the most similar to one another in both average height and MD width and could potentially cause confusion during identification.

Table 4.1. Average mesial-distal width and average height measured in mm across each species evaluated.

Species	Average MD Width	Average Height
Carcharodon carcharias	22.96	22.23
Galeocerdo cuvier	13.01	8.57
Carcharhinus leucas	17.25	13.08
Prionace glauca	12.07	12.88
Negaprion brevirostris	12.28	21.01
Carcharhinus melanopterus	11.28	9.92
Carcharhinus obscurus	8.13	8.32
Carcharhinus amboinensis	11.53	8.90
Carcharhinus amblyrhynchos	13.24	9.88
Carcharias taurus	12.78	12.95
Isistius brasiliensis	2.95	6.35
Nebrius ferrugineus	Could not measure	Could not measure

A scatterplot of tooth dimensions is presented in Figure 4.1. The white shark is separated from the rest of the species, and is the only species that can be easily distinguished from the others. The tiger shark and the bull shark form smaller clusters near the center of the graph. There is significant overlap between the rest of the species

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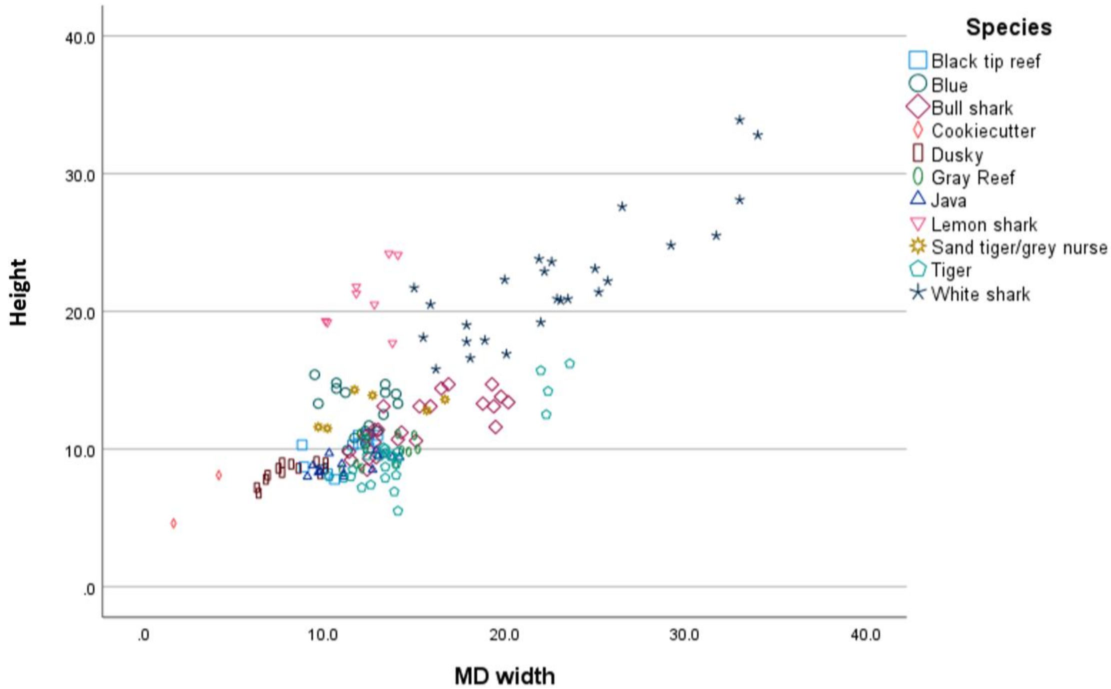

Figure 4.1. Scatterplot of MD width and overall height of teeth by each species.

Serrated and Nonserrated Teeth

Table 4.2 presents the distribution of serrated and nonserrated teeth among the 12 species analyzed. The gray reef shark is the most unique in this category. Serrations are only located on one edge of their teeth, and the other edge is nonserrated. This is the only species examined in the present study in which the pattern differs on an individual tooth. The black tip reef shark and the blue shark are also unique, because they have differing categories based on where the tooth is located. For both species, the teeth in their upper jaws are serrated, while the teeth in their lower jaws are not. This also resulted in the species having different striation pattern classification types from the upper and lower jaw. In these two species, the overall pattern classification type was based on their serrated teeth.

Table 4.2. Serrated vs. nonserrated teeth.

Species	Serrated or Nonserrated
White Shark	Serrated
Tiger Shark	Serrated
Bull Shark	Serrated
Blue Shark	Serrated
Lemon Shark	Nonserrated
Blacktip Reef Shark	Serrated
Dusky Shark	Serrated
Java Shark	Serrated
Gray Reef Shark	Serrated
Sand Tiger Shark	Nonserrated
Cookiecutter Shark	Nonserrated
Tawny Nurse Shark	Nonserrated

Photographs of the mandibles from each of the twelve species that are included in the present study can be found in Figure 4.2.

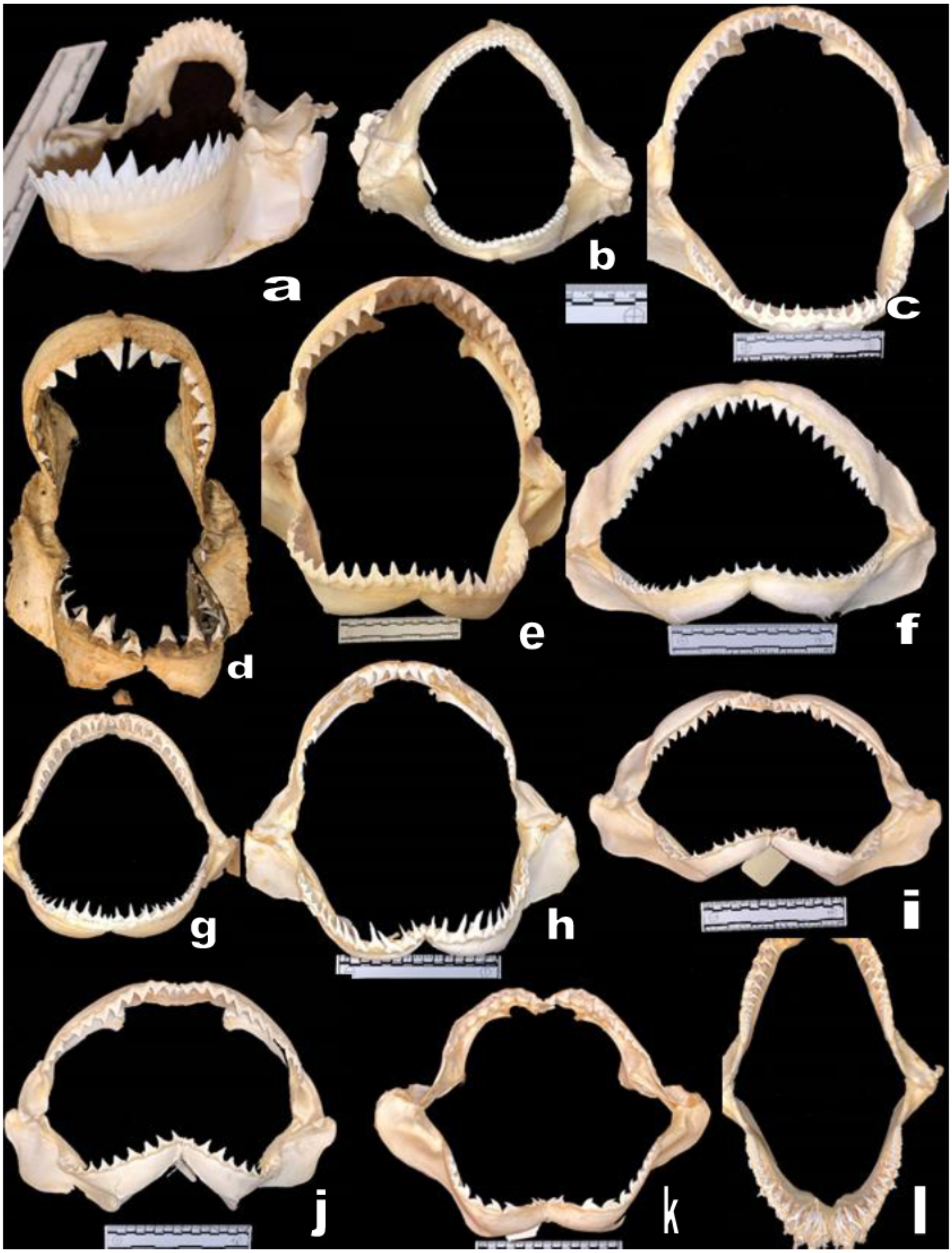

Figure 4.2. Mandibles of the twelve shark species studied: (a) cookiecutter, (b) tawny nurse, (c) gray reef, (d) white, (e) bull, (f) blacktip reef, (g) lemon, (h) blue, (i) dusky, (j) java, (k) tiger, and (l) sand tiger.

Statistical Analysis

Tooth and Striation Morphology

Independent samples Kruskal-Wallis tests were used to analyze most of the data. The corresponding parametric test is an ANOVA, which was first run to determine whether an ANOVA or Kruskal-Wallis test would better represent the data (Knapp 2018). When using ANOVA as the statistical test for data, the p-value for the test for homogeneity of variances should not be significant; these values should be similar to one another and not statistically significant because it means that the groups of data are similar and can be compared. If the test for homogeneity of variances is run and the p-values are statistically significant, then it becomes clear that the categories of data being compared are already different from one another, so the results of the ANOVA are meaningless. When this is the case, a Kruskal-Wallis test should be used instead (Knapp 2018).

In an effort to establish the fact that the species in this present study differ from one another in their tooth size, tooth morphology, and striation pattern, several different independent samples Kruskal-Wallis with Bonferroni post hoc tests were conducted. The first pair of data that were tested were the upper and lower bitemark circumferences in which all twelve species were utilized (Table 4.3). Both the upper BC and lower BC Kruskal-Wallis tests rejected the null hypothesis that stated the distribution of upper and lower bite circumference are the same across categories of species. The null hypothesis was rejected, because the p-values, or the significance values were 0.000 at the 0.05 alpha level.

The pairwise comparisons were used to analyze each individual for each upper and lower BC, along with the adjusted significance from the Bonferroni post hoc tests (Tables 4.4 and 4.5). The species significantly different were: cookiecutter/white, blacktip reef/blue, blacktip reef/gray reef, blacktip reef/lemon, blacktip reef/bull, blacktip reef/sand tiger, blacktip reef/tiger, blacktip reef/white, dusky/gray reef, dusky/lemon, dusky/bull, dusky/sand tiger, dusky/white, tiger/bull, tiger/white, java/white, java/blue, java/tiger, java/lemon, java/gray reef, java/bull, java/sand tiger, blue/sand tiger, and blue/white.

Table 4.3. Independent samples Kruskal-Wallis test for upper BC and lower BC across species.

Test Statistic	Upper BC	Lower BC
Total N	154	154
Test Statistic	134.427[a]	139.712[a]
Degree of Freedom	11	11
Asymptotic Sig (2-sided test)	0.000	0.000

a. The test statistic is adjusted for ties.

Table 4.4. Pairwise comparisons from the independent Kruskal-Wallis test of upper BC across species.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Cookiecutter-Tawny Nurse	-1.500	54.411	-.028	.978	1.000
Cookiecutter-Black tip reef	8.500	33.744	.252	.801	1.000
Cookiecutter-Dusky	-21.500	33.744	-.637	.524	1.000
Cookiecutter-Tiger	-53.140	32.647	-1.628	.104	1.000
Cookiecutter-Java	-56.000	33.583	-1.668	.095	1.000
Cookiecutter-Blue	71.000	33.320	2.131	.033	1.000
Cookiecutter-Gray Reef	-95.000	33.931	-2.800	.005	.338
Cookiecutter-Lemon shark	-104.000	36.274	-2.867	.004	.273
Cookiecutter-Bull shark	105.196	32.752	3.212	.001	.087
Cookiecutter-Sand tiger shark	-111.000	35.122	-3.160	.002	.104
Cookiecutter-White shark	-142.500	32.876	-4.334	.000	.001
Tawny Nurse-Black tip reef	7.000	46.103	.152	.879	1.000
Tawny Nurse-Dusky	20.000	46.103	.434	.664	1.000
Tawny Nurse-Tiger	-51.640	45.306	-1.140	.254	1.000
Tawny Nurse-Java	54.500	45.986	1.185	.236	1.000
Tawny Nurse-Blue	69.500	45.794	1.518	.129	1.000
Tawny Nurse-Gray Reef	93.500	46.240	2.022	.043	1.000
Tawny Nurse-Lemon shark	102.500	47.986	2.136	.033	1.000
Tawny Nurse-Bull shark	103.696	45.382	2.285	.022	1.000
Tawny Nurse-Sand tiger shark	109.500	47.121	2.324	.020	1.000
Tawny Nurse-White shark	-141.000	45.472	-3.101	.002	.127
Black tip reef-Dusky	-13.000	17.425	-.746	.456	1.000
Black tip reef-Tiger	-44.640	15.191	-2.939	.003	.218
Black tip reef-Java	-47.500	17.111	-2.776	.006	.363
Black tip reef-Blue	-62.500	16.589	-3.768	.000	.011
Black tip reef-Gray Reef	-86.500	17.785	-4.864	.000	.000
Black tip reef-Lemon shark	-95.500	21.927	-4.355	.000	.001
Black tip reef-Bull shark	-96.696	15.415	-6.273	.000	.000
Black tip reef-Sand tiger shark	-102.500	19.963	-5.134	.000	.000

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Black tip reef-White shark	-134.000	15.678	-8.547	.000	.000
Dusky-Tiger	-31.640	15.191	-2.083	.037	1.000
Dusky-Java	-34.500	17.111	-2.016	.044	1.000
Dusky-Blue	49.500	16.589	2.984	.003	.188
Dusky-Gray Reef	-73.500	17.785	-4.133	.000	.002
Dusky-Lemon shark	-82.500	21.927	-3.763	.000	.011
Dusky-Bull shark	83.696	15.415	5.429	.000	.000
Dusky-Sand tiger shark	-89.500	19.963	-4.483	.000	.000
Dusky-White shark	-121.000	15.678	-7.718	.000	.000
Tiger-Java	2.860	14.830	.193	.847	1.000
Tiger-Blue	17.860	14.223	1.256	.209	1.000
Tiger-Gray Reef	41.860	15.602	2.683	.007	.482
Tiger-Lemon shark	50.860	20.196	2.518	.012	.778
Tiger-Bull shark	52.056	12.836	4.055	.000	.003
Tiger-Sand tiger shark	57.860	18.046	3.206	.001	.089
Tiger-White shark	-89.360	13.150	-6.795	.000	.000
Java-Blue	15.000	16.258	.923	.356	1.000
Java-Gray Reef	39.000	17.477	2.231	.026	1.000
Java-Lemon shark	-48.000	21.678	-2.214	.027	1.000
Java-Bull shark	49.196	15.060	3.267	.001	.072
Java-Sand tiger shark	-55.000	19.690	-2.793	.005	.344
Java-White shark	-86.500	15.329	-5.643	.000	.000
Blue-Gray Reef	-24.000	16.966	-1.415	.157	1.000
Blue-Lemon shark	-33.000	21.267	-1.552	.121	1.000
Blue-Bull shark	-34.196	14.463	-2.364	.018	1.000
Blue-White shark	-71.500	14.743	-4.850	.000	.000
Gray Reef-Lemon shark	-9.000	22.213	-.405	.685	1.000
Gray Reef-Bull shark	10.196	15.820	.644	.519	1.000
Gray Reef-Sand tiger shark	-16.000	20.278	-.789	.430	1.000
Gray Reef-White shark	-47.500	16.077	-2.955	.003	.207
Lemon shark-Bull shark	1.196	20.366	.059	.953	1.000
Sand tiger/grey nurse-Lemon shark	7.000	23.993	.292	.770	1.000
Lemon shark-White shark	-38.500	20.565	-1.872	.061	1.000
Bull shark-Sand tiger shark	-5.804	18.235	-.318	.750	1.000
Bull shark-White shark	-37.304	13.409	-2.782	.005	.357
Sand tiger shark-White shark	-31.500	18.458	-1.707	.088	1.000

Table 4.5. Pairwise comparison from the independent Kruskal-Wallis test of lower BC across species.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Tawny Nurse-Cookiecutter	1.500	54.411	.028	.978	1.000
Tawny Nurse-Java	9.500	45.986	.207	.836	1.000
Tawny Nurse-Black tip reef	23.000	46.103	.499	.618	1.000
Tawny Nurse-Dusky	36.000	46.103	.781	.435	1.000
Tawny Nurse-Blue	50.500	45.794	1.103	.270	1.000
Tawny Nurse-Tiger	-80.440	45.306	-1.775	.076	1.000
Tawny Nurse-Lemon shark	92.500	47.986	1.928	.054	1.000
Tawny Nurse-Gray Reef	101.500	46.240	2.195	.028	1.000
Tawny Nurse-Bull shark	105.696	45.382	2.329	.020	1.000
Tawny Nurse-Sand tiger	111.500	47.121	2.366	.018	1.000
Tawny Nurse-White shark	-141.095	45.472	-3.103	.002	.126
Cookiecutter-Java	-8.000	33.583	-.238	.812	1.000
Cookiecutter-Black tip reef	21.500	33.744	.637	.524	1.000
Cookiecutter-Dusky	-34.500	33.744	-1.022	.307	1.000
Cookiecutter-Blue	49.000	33.320	1.471	.141	1.000
Cookiecutter-Tiger	-78.940	32.647	-2.418	.016	1.000
Cookiecutter-Lemon shark	-91.000	36.274	-2.509	.012	.800
Cookiecutter-Gray Reef	-100.000	33.931	-2.947	.003	.212
Cookiecutter-Bull shark	104.196	32.752	3.181	.001	.097
Cookiecutter-Sand tiger	-110.000	35.122	-3.132	.002	.115
Cookiecutter-White shark	-139.595	32.876	-4.246	.000	.001
Java-Black tip reef	13.500	17.111	.789	.430	1.000
Java-Dusky	26.500	17.111	1.549	.121	1.000
Java-Blue	41.000	16.258	2.522	.012	.771
Java-Tiger	-70.940	14.830	-4.784	.000	.000
Java-Lemon shark	-83.000	21.678	-3.829	.000	.008
Java-Gray Reef	92.000	17.477	5.264	.000	.000
Java-Bull shark	96.196	15.060	6.388	.000	.000
Java-Sand tiger	-102.000	19.690	-5.180	.000	.000
Java-White shark	-131.595	15.329	-8.585	.000	.000
Black tip reef-Dusky	-13.000	17.425	-.746	.456	1.000
Black tip reef-Blue	-27.500	16.589	-1.658	.097	1.000
Black tip reef-Tiger	-57.440	15.191	-3.781	.000	.010

Sample 1-Sample 2	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adj. Sig.**
Black tip reef-Lemon shark	-69.500	21.927	-3.170	.002	.101
Black tip reef-Gray Reef	-78.500	17.785	-4.414	.000	.001
Black tip reef-Bull shark	-82.696	15.415	-5.364	.000	.000
Black tip reef-Sand tiger	-88.500	19.963	-4.433	.000	.001
Black tip reef-White shark	-118.095	15.678	-7.532	.000	.000
Dusky-Blue	14.500	16.589	.874	.382	1.000
Dusky-Tiger	-44.440	15.191	-2.925	.003	.227
Dusky-Lemon shark	-56.500	21.927	-2.577	.010	.658
Dusky-Gray Reef	-65.500	17.785	-3.683	.000	.015
Dusky-Bull shark	69.696	15.415	4.521	.000	.000
Dusky-Sand tiger	-75.500	19.963	-3.782	.000	.010
Dusky-White shark	-105.095	15.678	-6.703	.000	.000
Blue-Tiger	-29.940	14.223	-2.105	.035	1.000
Blue-Lemon shark	-42.000	21.267	-1.975	.048	1.000
Blue-Gray Reef	-51.000	16.966	-3.006	.003	.175
Blue-Bull shark	-55.196	14.463	-3.816	.000	.009
Blue-Sand tiger	-61.000	19.237	-3.171	.002	.100
Blue-White shark	-90.595	14.743	-6.145	.000	.000
Tiger-Lemon shark	12.060	20.196	.597	.550	1.000
Tiger-Gray Reef	21.060	15.602	1.350	.177	1.000
Tiger-Bull shark	25.256	12.836	1.968	.049	1.000
Tiger-Sand tiger	31.060	18.046	1.721	.085	1.000
Tiger-White shark	-60.655	13.150	-4.612	.000	.000
Lemon shark-Gray Reef	9.000	22.213	.405	.685	1.000
Lemon shark-Bull shark	13.196	20.366	.648	.517	1.000
Sand tiger/grey nurse-Lemon shark	19.000	23.993	.792	.428	1.000
Lemon shark-White shark	-48.595	20.565	-2.363	.018	1.000
Gray Reef-Bull shark	4.196	15.820	.265	.791	1.000
Gray Reef-Sand tiger	-10.000	20.278	-.493	.622	1.000
Gray Reef-White shark	-39.595	16.077	-2.463	.014	.910
Bull shark-Sand tiger	-5.804	18.235	-.318	.750	1.000
Bull shark-White shark	-35.400	13.409	-2.640	.008	.547
Sand tiger-White shark	-29.595	18.458	-1.603	.109	1.000

The next sets of data that were analyzed using an independent samples Kruskal-Wallis test were tooth height and mesial-distal tooth width (Table 4.6). The null hypothesis stated that the distribution of tooth height and MD width is the same across categories of species. With p-values of 0.000 and alpha at 0.05, the null hypothesis was rejected. Tooth height and MD width were statistically different.

Table 4.6. Independent samples Kruskal-Wallis test for tooth height and MD width across species.

Test Statistic	Tooth Height	Tooth MD Width
Total N	158	158
Test Statistic	119.999[a]	102.688[a]
Degree of Freedom	10	10
Asymptotic Sig (2-sided test)	0.000	0.000

a. The test statistic is adjusted for ties.

The pairwise comparisons were run between each individual for tooth height and MD width, along with the adjusted significance from the Bonferroni post hoc tests (Tables 4.7 and 4.8). The species significantly different were: cookiecutter/sand tiger, cookiecutter/white, dusky/bull, dusky/blue, dusky/lemon, dusky/sand tiger, dusky/gray reef, dusky/tiger, dusky/white, java/blue, java/ sand tiger, java/white, tiger/blue, tiger/ sand tiger, tiger/white, blacktip reef/ sand tiger, blacktip reef/white, gray reef/ sand tiger, gray reef/white, blue/white, sand tiger/white, sand tiger/white and bull/white.

Table 4.7. Pairwise comparisons from the independent Kruskal-Wallis test of tooth height across species.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Cookiecutter-Dusky	-17.077	34.749	-.491	.623	1.000
Cookiecutter-Java	-28.357	34.583	-.820	.412	1.000
Cookiecutter-Tiger	-37.160	33.619	-1.105	.269	1.000
Cookiecutter-Black tip reef	51.077	34.749	1.470	.142	1.000
Cookiecutter-Gray Reef	-51.375	34.942	-1.470	.141	1.000
Cookiecutter-Bull shark	77.130	33.727	2.287	.022	1.000
Cookiecutter-Blue	91.688	34.312	2.672	.008	.497
Cookiecutter-Lemon shark	-94.250	37.354	-2.523	.012	.768
Cookiecutter-Sand tiger	-131.125	36.168	-3.625	.000	.019
Cookiecutter-White shark	-132.885	33.571	-3.958	.000	.005
Dusky-Java	-11.280	17.621	-.640	.522	1.000
Dusky-Tiger	-20.083	15.644	-1.284	.199	1.000
Dusky-Black tip reef	34.000	17.944	1.895	.058	1.000
Dusky-Gray Reef	-34.298	18.314	-1.873	.061	1.000
Dusky-Bull shark	60.054	15.874	3.783	.000	.010
Dusky-Blue	74.611	17.083	4.368	.000	.001
Dusky-Lemon shark	-77.173	22.579	-3.418	.001	.042
Dusky-Sand tiger	-114.048	20.558	-5.548	.000	.000
Dusky-White shark	-115.808	15.540	-7.452	.000	.000
Java-Tiger	-8.803	15.272	-.576	.564	1.000
Java-Black tip reef	22.720	17.621	1.289	.197	1.000
Java-Gray Reef	23.018	17.998	1.279	.201	1.000
Java-Bull shark	48.773	15.508	3.145	.002	.110
Java-Blue	63.330	16.743	3.783	.000	.010
Java-Lemon shark	-65.893	22.323	-2.952	.003	.209
Java-Sand tiger	-102.768	20.276	-5.068	.000	.000
Java-White shark	-104.527	15.166	-6.892	.000	.000
Tiger-Black tip reef	13.917	15.644	.890	.374	1.000
Tiger-Gray Reef	14.215	16.067	.885	.376	1.000
Tiger-Bull shark	39.970	13.218	3.024	.002	.165
Tiger-Blue	54.528	14.647	3.723	.000	.013
Tiger-Lemon shark	57.090	20.798	2.745	.006	.399
Tiger-Sand tiger	93.965	18.583	5.056	.000	.000
Tiger-White shark	-95.725	12.815	-7.470	.000	.000
Black tip reef-Gray Reef	-.298	18.314	-.016	.987	1.000

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Black tip reef-Bull shark	-26.054	15.874	-1.641	.101	1.000
Black tip reef-Blue	-40.611	17.083	-2.377	.017	1.000
Black tip reef-Lemon shark	-43.173	22.579	-1.912	.056	1.000
Black tip reef-Sand tiger	-80.048	20.558	-3.894	.000	.007
Black tip reef-White shark	-81.808	15.540	-5.264	.000	.000
Gray Reef-Bull shark	25.755	16.292	1.581	.114	1.000
Gray Reef-Blue	40.313	17.471	2.307	.021	1.000
Gray Reef-Lemon shark	-42.875	22.875	-1.874	.061	1.000
Gray Reef-Sand tiger	-79.750	20.882	-3.819	.000	.009
Gray Reef-White shark	-81.510	15.966	-5.105	.000	.000
Bull shark-Blue	14.557	14.893	.977	.328	1.000
Bull shark-Lemon shark	-17.120	20.972	-.816	.414	1.000
Bull shark-Sand tiger	-53.995	18.778	-2.875	.004	.266
Bull shark-White shark	-55.754	13.096	-4.257	.000	.001
Blue-Lemon shark	-2.562	21.901	-.117	.907	1.000
Blue-Sand tiger	-39.437	19.810	-1.991	.047	1.000
Blue-White shark	-41.197	14.537	-2.834	.005	.303
Sand tiger/grey nurse-Lemon shark	36.875	24.707	1.492	.136	1.000
Lemon shark-White shark	-38.635	20.720	-1.865	.062	1.000
Sand tiger-White shark	-1.760	18.497	-.095	.924	1.000

Table 4.8. Pairwise comparisons from the independent Kruskal-Wallis test of MD tooth width across species.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Cookiecutter-Dusky	-10.154	34.748	-.292	.770	1.000
Cookiecutter-Black tip reef	44.577	34.748	1.283	.200	1.000
Cookiecutter-Java	-50.607	34.582	-1.463	.143	1.000
Cookiecutter-Blue	58.781	34.311	1.713	.087	1.000
Cookiecutter-Sand tiger	-63.750	36.167	-1.763	.078	1.000
Cookiecutter-Lemon shark	-67.000	37.353	-1.794	.073	1.000
Cookiecutter-Gray Reef	-80.083	34.940	-2.292	.022	1.000
Cookiecutter-Tiger	-88.660	33.617	-2.637	.008	.552
Cookiecutter-Bull shark	97.978	33.726	2.905	.004	.242
Cookiecutter-White	-139.250	33.570	-4.148	.000	.002

Sample 1-Sample 2	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Sig.**	**Adj. Sig.**
shark					
Dusky-Black tip reef	34.423	17.944	1.918	.055	1.000
Dusky-Java	-40.453	17.620	-2.296	.022	1.000
Dusky-Blue	48.627	17.082	2.847	.004	.292
Dusky-Sand tiger	-53.596	20.557	-2.607	.009	.603
Dusky-Lemon shark	-56.846	22.579	-2.518	.012	.780
Dusky-Gray Reef	-69.929	18.314	-3.818	.000	.009
Dusky-Tiger	-78.506	15.643	-5.019	.000	.000
Dusky-Bull shark	87.824	15.874	5.533	.000	.000
Dusky-White shark	-129.096	15.540	-8.308	.000	.000
Black tip reef-Java	-6.030	17.620	-.342	.732	1.000
Black tip reef-Blue	-14.204	17.082	-.832	.406	1.000
Black tip reef-Sand tiger	-19.173	20.557	-.933	.351	1.000
Black tip reef-Lemon shark	-22.423	22.579	-.993	.321	1.000
Black tip reef-Gray Reef	-35.506	18.314	-1.939	.053	1.000
Black tip reef-Tiger	-44.083	15.643	-2.818	.005	.319
Black tip reef-Bull shark	-53.401	15.874	-3.364	.001	.051
Black tip reef-White shark	-94.673	15.540	-6.092	.000	.000
Java-Blue	8.174	16.742	.488	.625	1.000
Java-Sand tiger	-13.143	20.275	-.648	.517	1.000
Java-Lemon shark	-16.393	22.323	-.734	.463	1.000
Java-Gray Reef	29.476	17.997	1.638	.101	1.000
Java-Tiger	-38.053	15.271	-2.492	.013	.839
Java-Bull shark	47.371	15.507	3.055	.002	.149
Java-White shark	-88.643	15.165	-5.845	.000	.000
Blue-Sand tiger	-4.969	19.809	-.251	.802	1.000
Blue-Lemon shark	-8.219	21.900	-.375	.707	1.000
Blue-Gray Reef	-21.302	17.470	-1.219	.223	1.000
Blue-Tiger	-29.879	14.646	-2.040	.041	1.000
Blue-Bull shark	-39.197	14.893	-2.632	.008	.560
Blue-White shark	-80.469	14.536	-5.536	.000	.000
Lemon shark-Sand tiger/grey nurse	-3.250	24.707	-.132	.895	1.000
Sand tiger-Gray Reef	16.333	20.881	.782	.434	1.000
Sand tiger-Tiger	-24.910	18.583	-1.340	.180	1.000
Sand tiger-Bull shark	34.228	18.778	1.823	.068	1.000
Sand tiger-White shark	-75.500	18.496	-4.082	.000	.003
Lemon shark-Gray Reef	13.083	22.874	.572	.567	1.000

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Lemon shark-Tiger	-21.660	20.797	-1.041	.298	1.000
Lemon shark-Bull shark	30.978	20.971	1.477	.140	1.000
Lemon shark-White shark	-72.250	20.720	-3.487	.000	.032
Gray Reef-Tiger	-8.577	16.066	-.534	.593	1.000
Gray Reef-Bull shark	17.895	16.291	1.098	.272	1.000
Gray Reef-White shark	-59.167	15.966	-3.706	.000	.014
Tiger-Bull shark	9.318	13.218	.705	.481	1.000
Tiger-White shark	-50.590	12.814	-3.948	.000	.005
Bull shark-White shark	-41.272	13.095	-3.152	.002	.107

Because the tooth height and tooth MD width are not the same across categories of species, the striation height (the measurement of the tooth margin that is serrated and created the striation impression, i.e., the perimeter of the outside of the tooth) of the wax impressions should also not be the same across categories of species. A follow-up Kruskal-Wallis test for the striation height was conducted (Table 4.9). The null hypothesis stated that the distribution of striation height is the same across categories of species. The resulting p-values are 0.000 and the alpha was 0.05, indicating that the null hypothesis should be rejected, and that the difference in striation height across categories of species is statistically significant.

Table 4.9. Independent samples Kruskal-Wallis test for striation height across species.

Test Statistic	Striation Height
Total N	145
Test Statistic	85.962[a]
Degree of Freedom	8
Asymptotic Sig (2-sided test)	0.000

a. The test statistic is adjusted for ties.

The pairwise comparisons were run between each individual for striation height, along with the adjusted significance from the Bonferroni post hoc tests (Table 4.10). The species significantly different were: dusky/bull, dusky/blue, dusky/white, blacktip reef/white, java/white, tiger/white, gray reef/white, bull/white, and blue/white.

Table 4.10. Pairwise comparisons from the independent Kruskal-Wallis test of striation height across species.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Dusky-Black tip reef	13.308	16.474	.808	.419	1.000
Dusky-Java	-14.459	16.178	-.894	.371	1.000
Dusky-Tiger	-15.243	14.362	-1.061	.289	1.000
Dusky-Gray Reef	-38.965	16.814	-2.317	.020	1.000
Dusky-Bull shark	49.858	14.574	3.421	.001	.041
Dusky-Blue	53.173	15.683	3.390	.001	.046
Dusky-Sand tiger	-65.423	26.903	-2.432	.015	.991
Dusky-White shark	-99.558	14.267	-6.978	.000	.000
Black tip reef-Java	-1.151	16.178	-.071	.943	1.000
Black tip reef-Tiger	-1.935	14.362	-.135	.893	1.000
Black tip reef-Gray Reef	-25.657	16.814	-1.526	.127	1.000

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Black tip reef-Bull shark	-36.550	14.574	-2.508	.012	.802
Black tip reef-Blue	-39.865	15.683	-2.542	.011	.728
Black tip reef-Sand tiger	-52.115	26.903	-1.937	.053	1.000
Black tip reef-White shark	-86.250	14.267	-6.045	.000	.000
Java-Tiger	-.784	14.021	-.056	.955	1.000
Java-Gray Reef	24.506	16.523	1.483	.138	1.000
Java-Bull shark	35.399	14.238	2.486	.013	.852
Java-Blue	38.714	15.371	2.519	.012	.778
Java-Sand tiger	-50.964	26.722	-1.907	.056	1.000
Java-White shark	-85.099	13.923	-6.112	.000	.000
Tiger-Gray Reef	23.722	14.750	1.608	.108	1.000
Tiger-Bull shark	34.615	12.135	2.852	.004	.286
Tiger-Blue	37.930	13.447	2.821	.005	.316
Tiger-Sand tiger	50.180	25.663	1.955	.051	1.000
Tiger-White shark	-84.315	11.765	-7.167	.000	.000
Gray Reef-Bull shark	10.893	14.957	.728	.466	1.000
Gray Reef-Blue	14.208	16.040	.886	.376	1.000
Gray Reef-Sand tiger	-26.458	27.112	-.976	.329	1.000
Gray Reef-White shark	-60.593	14.658	-4.134	.000	.002
Bull shark-Blue	3.315	13.673	.242	.808	1.000
Bull shark-Sand tiger	-15.565	25.783	-.604	.546	1.000
Bull shark-White shark	-49.700	12.023	-4.134	.000	.002
Blue-Sand tiger	-12.250	26.425	-.464	.643	1.000
Blue-White shark	-46.385	13.346	-3.476	.001	.034
Sand tiger-White shark	-34.135	25.610	-1.333	.183	1.000

Distribution of Pattern Type

The species were classified type by their serrations and corresponding striation patterns (Table 4.11 and Figure 4.3). Although some species belonged to two different pattern classifications, most of the species had a majority of one type of pattern over any others. The only exception was the white shark, as it was the only species to spread across two different pattern classification types, while being the *only* species belonging to those two pattern classifications.

Table 4.11. Pattern classification type and the corresponding species.

Pattern Classification Type	Number of Species	Species
0	5	Cookiecutter shark, tawny nurse shark, blue shark, blacktip reef shark, and lemon shark
0.5	1	Sand tiger shark
1.0	5	Blacktip reef shark, blue shark, bull shark, dusky shark, and java shark
1.5	4	Bull shark, dusky shark, gray reef shark, and java shark
2.0	0	N/A
2.5	1	Tiger shark
3.0	1	White shark
3.5	1	White shark

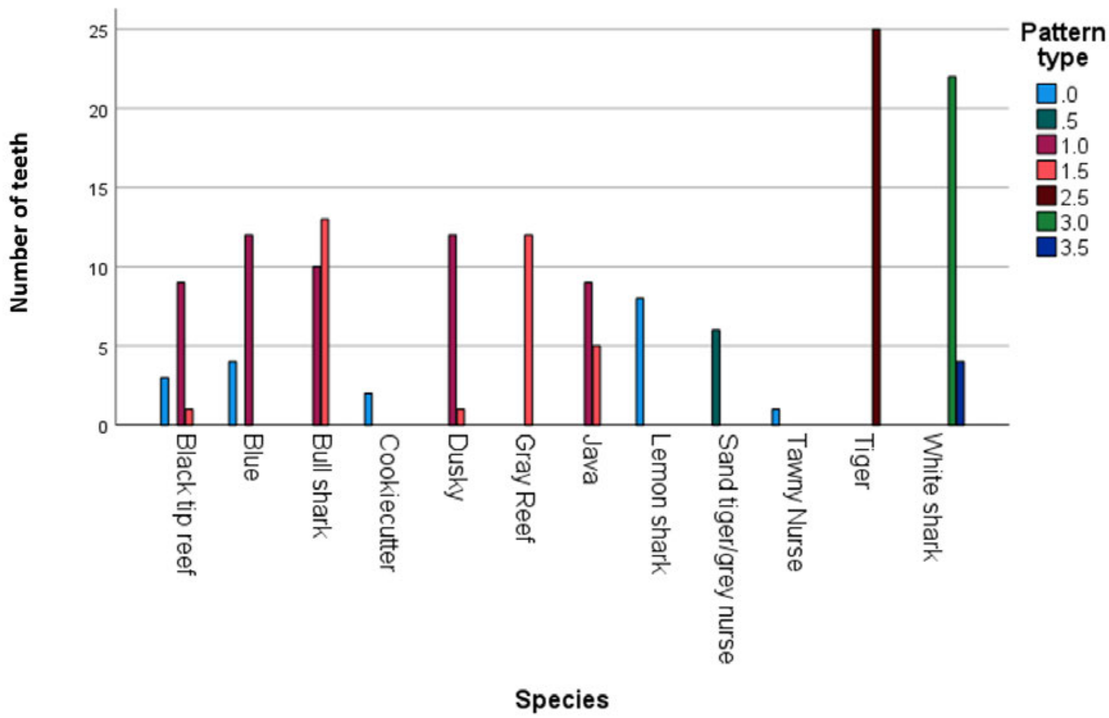

Figure 4.3. Distribution of species vs. pattern type.

The cookiecutter, tawny nurse, and sand tiger sharks are three of the four species that were exclusively nonserrated, so were classified as a 0 (Figure 4.4). The lemon shark also has nonerrated teeth, but the impressions left by the specimen were unique because it left an ultra-fine pattern in the wax when compared to the smooth impressions left by the other nonserrated species, so they were classified as a 0.5.

Blacktip reef, blue, dusky, and java sharks all were placed in the 1.0 category, which means they had small mamelon sizes and had a uniform pattern when the impressions were taken (Figures 4.5-4.8). These four species also clustered together on the scatterplot of average height and MD width (Figure 4.1). The bull shark and the gray reef shark were the only two species that were classified as a 1.5, meaning they had small mamelon sizes and an interrupted striation pattern (Figures 4.9 and 4.10).

There were no species that were placed in the 2.0 category, and the only species that was classified as a 2.5 was the tiger shark. Based on the hook-like morphology of tiger shark teeth, it was difficult to obtain a uniform or uninterrupted pattern when taking the striation impressions. No other species besides the tiger shark had such large or defined mamelons, which placed it in the 2.0-2.5 size range.

The white shark had the largest teeth out of the species studied, and was the only species to obtain a classification of 3.0 and 3.5. Most of the white shark teeth examined were placed in the 3.0 category, indicating a large mamelon size with a uniform pattern to the striation impressions. The only teeth from the white shark that were classified as 3.5 were slightly chipped from postmortem damage.

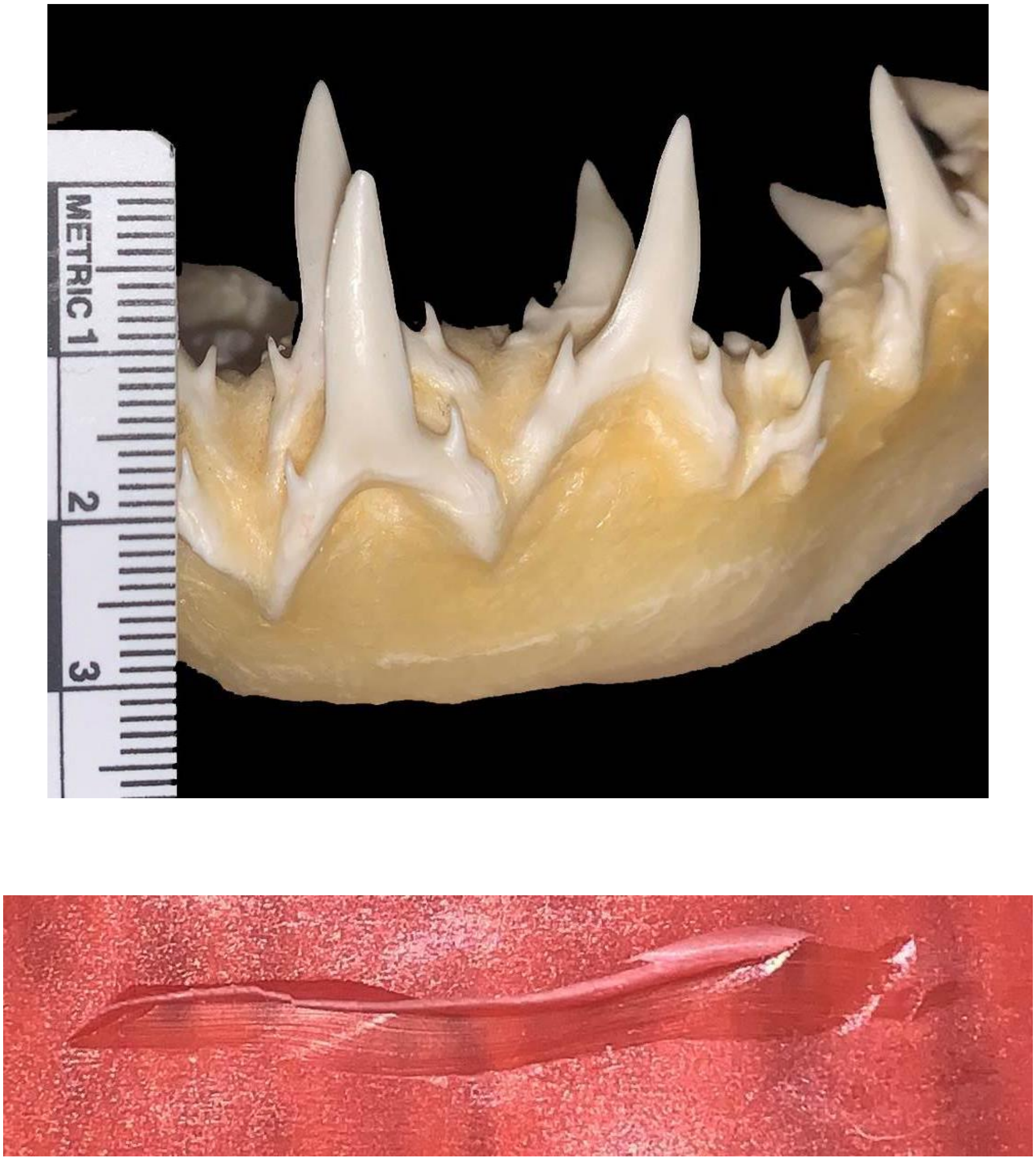

Figure 4.4. Classification of 0, sand tiger shark, (top image) individual tooth and (bottom image) striation pattern in wax.

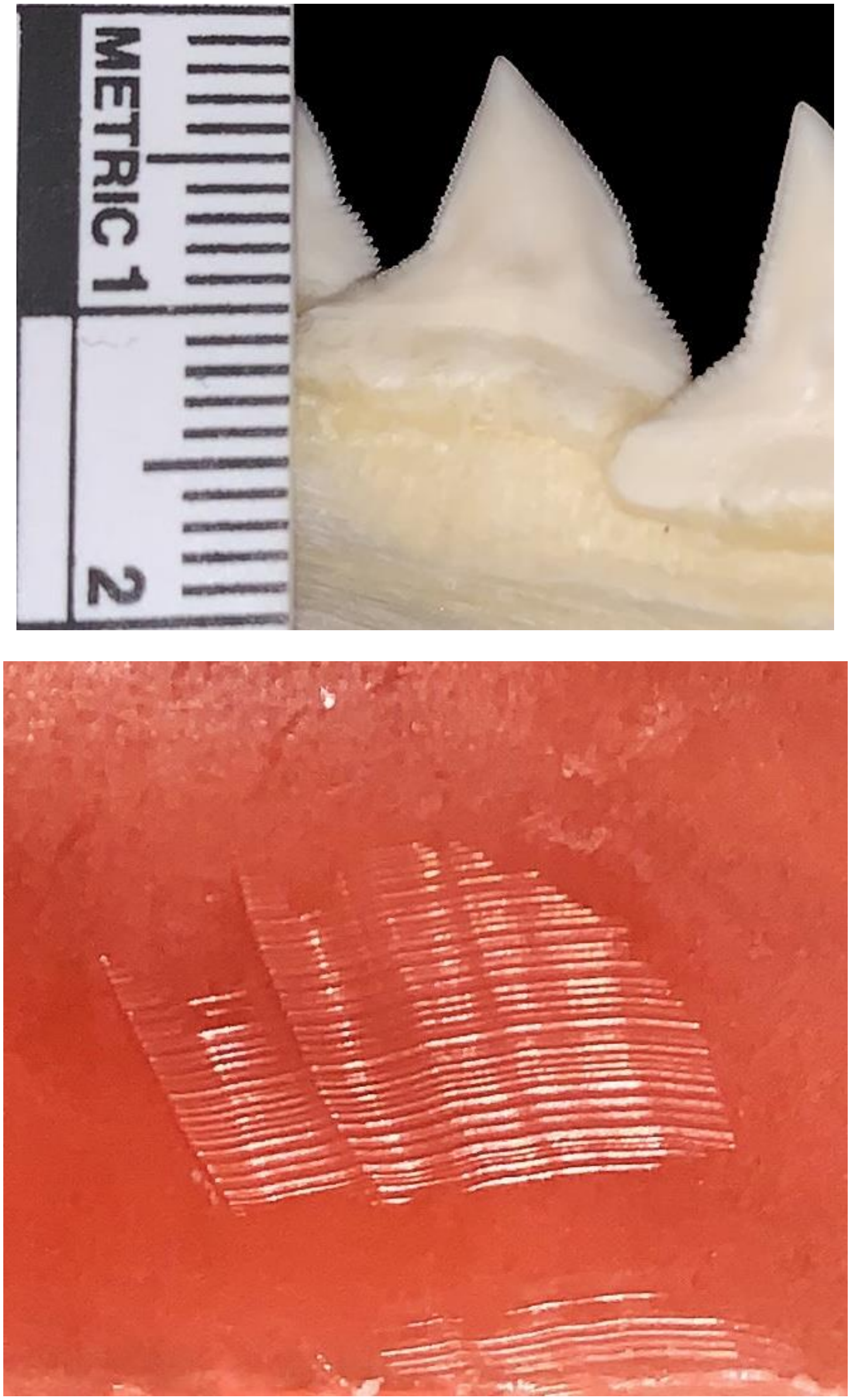

Figure 4.5. Classification of 1.0, blacktip reef shark, (top image) individual tooth and (bottom image) striation pattern in wax.

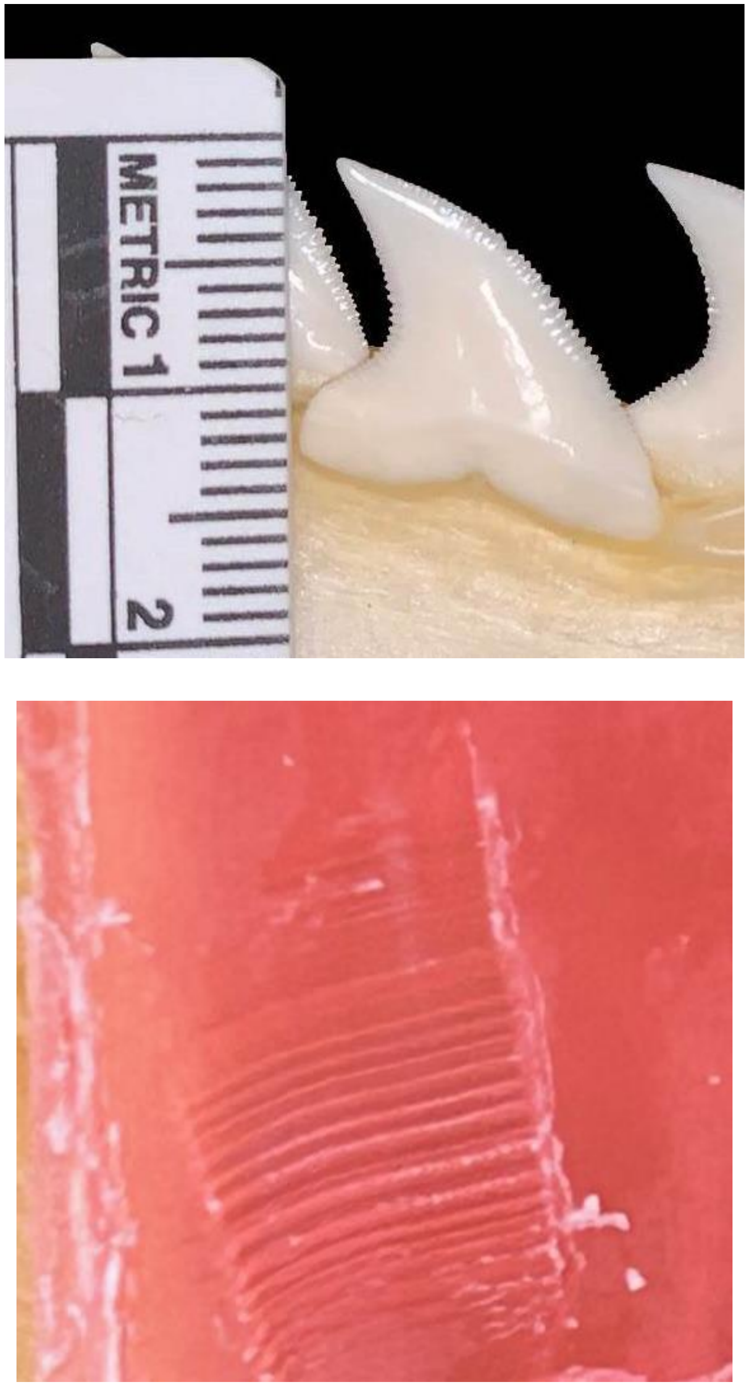

Figure 4.6. Classification of 1.0, blue shark, (top image) individual tooth and (bottom image) striation pattern in wax.

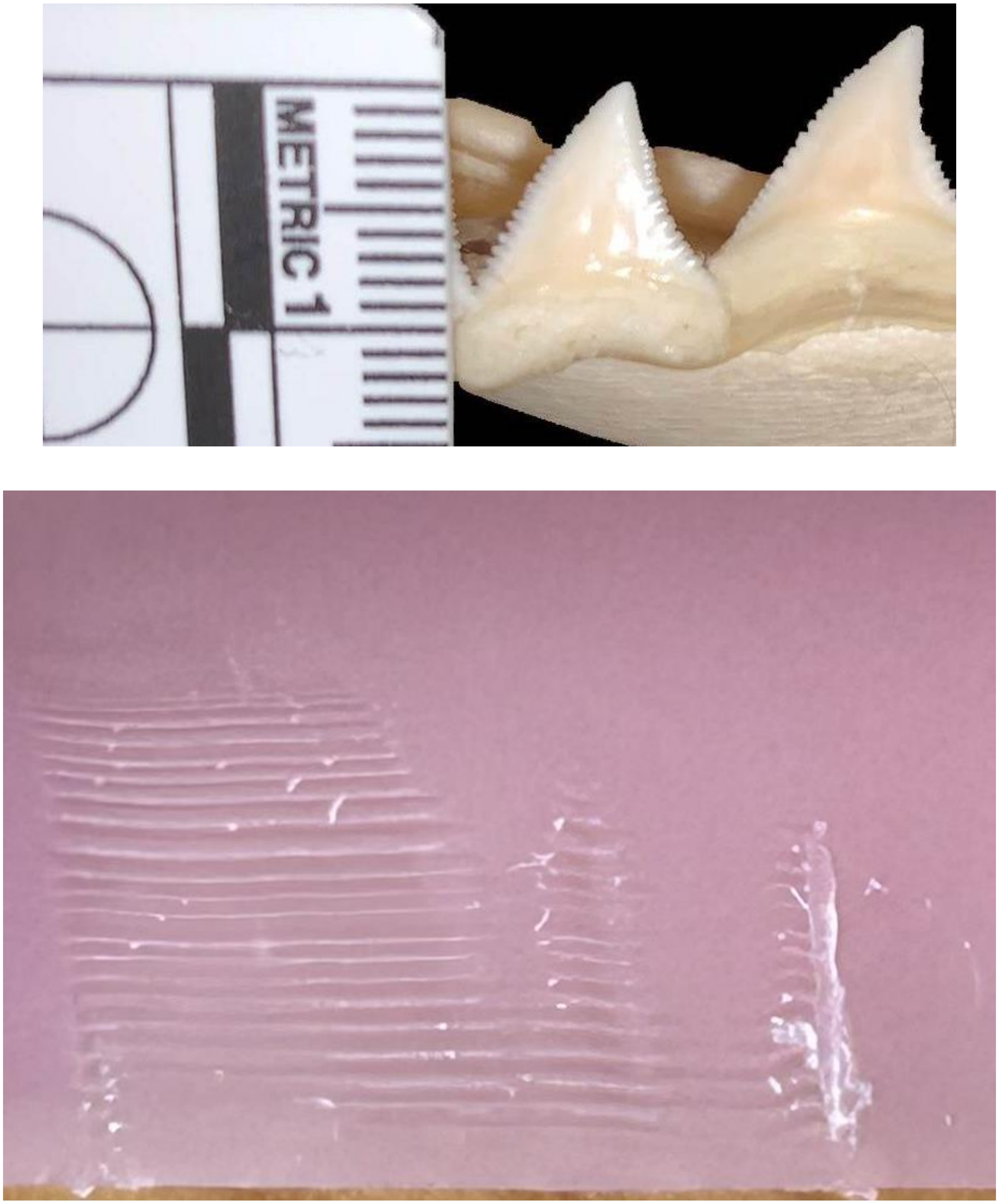

Figure 4.7. Classification of 1.0, dusky shark, (top image) individual tooth and (bottom image) striation pattern in wax.

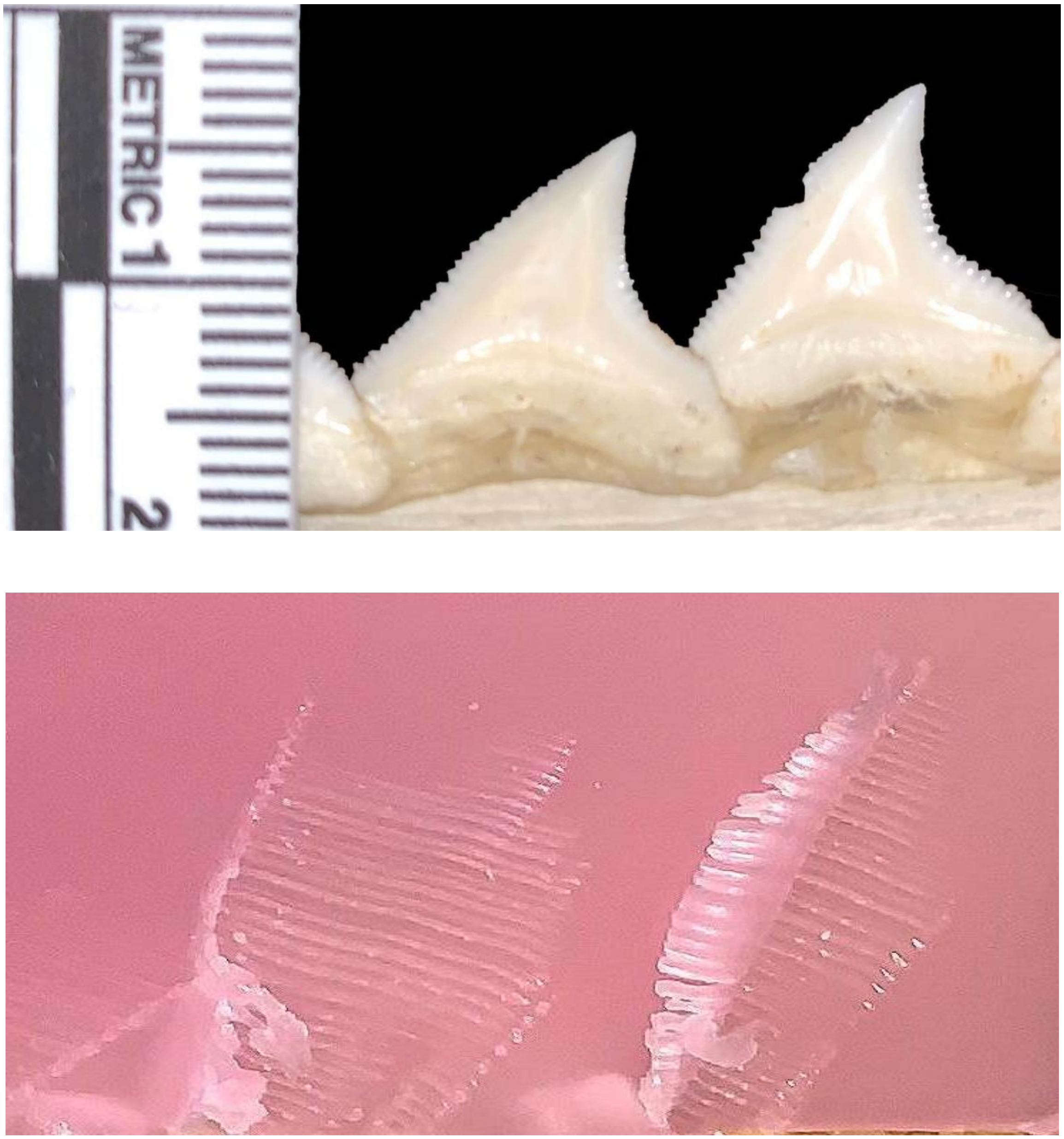

Figure 4.8. Classification of 1.0, java shark, (top image) individual tooth and (bottom image) striation pattern in wax.

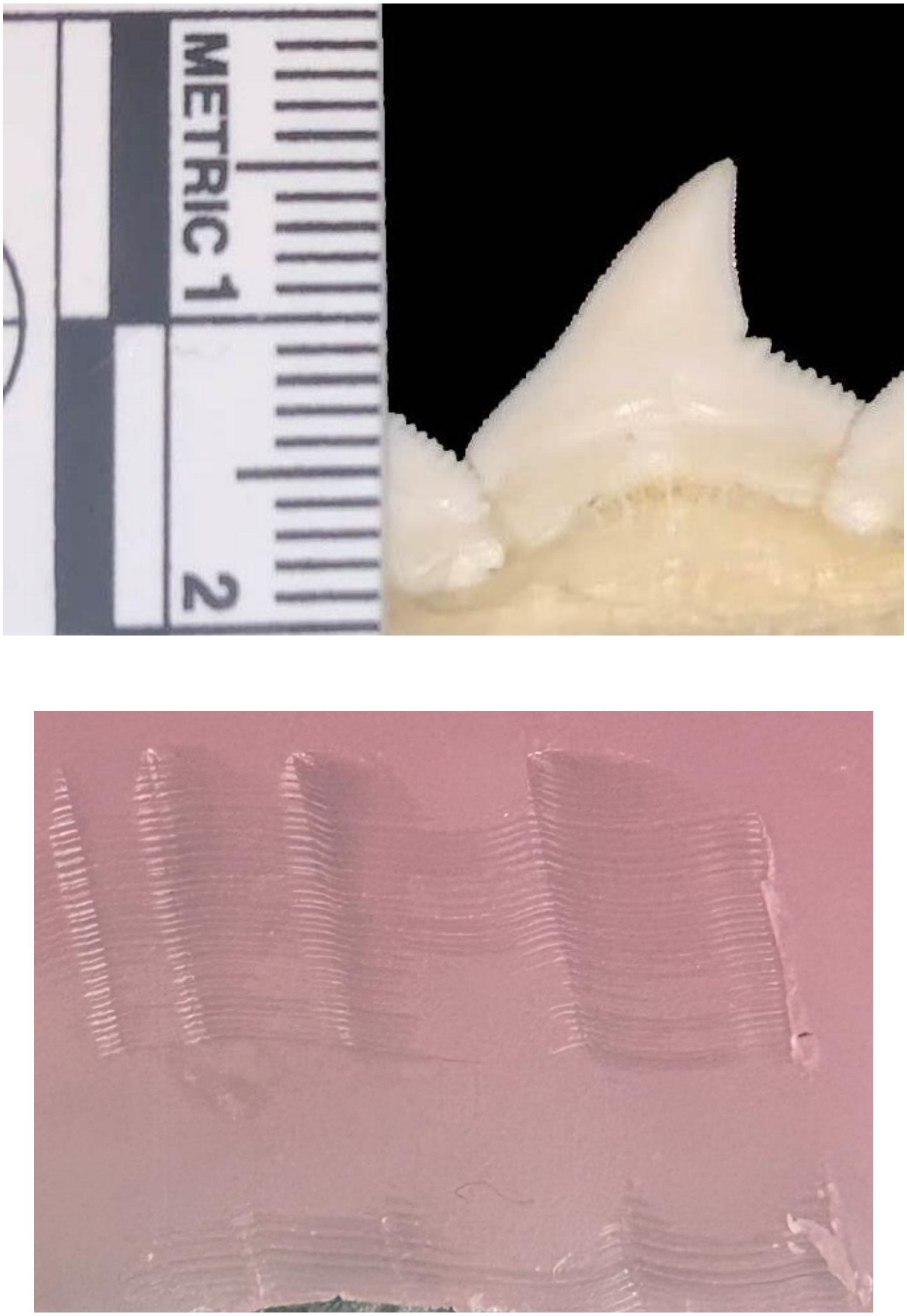

Figure 4.9. Classification of 1.5, gray reef shark, (top image) individual tooth and (bottom image) striation pattern in wax.

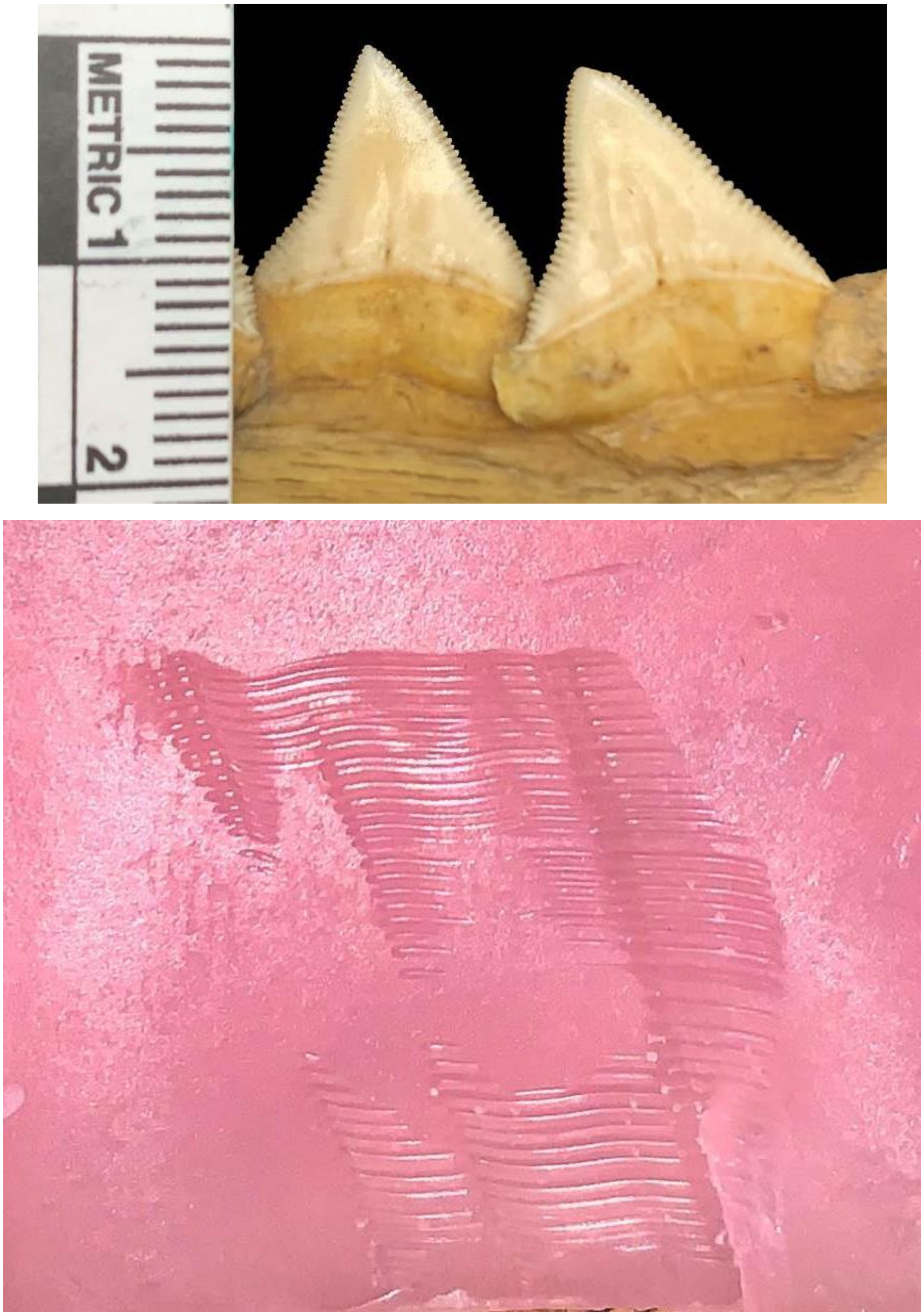

Figure 4.10. Classification of 1.5, bull shark, (top image) individual tooth and (bottom image) striation pattern in wax.

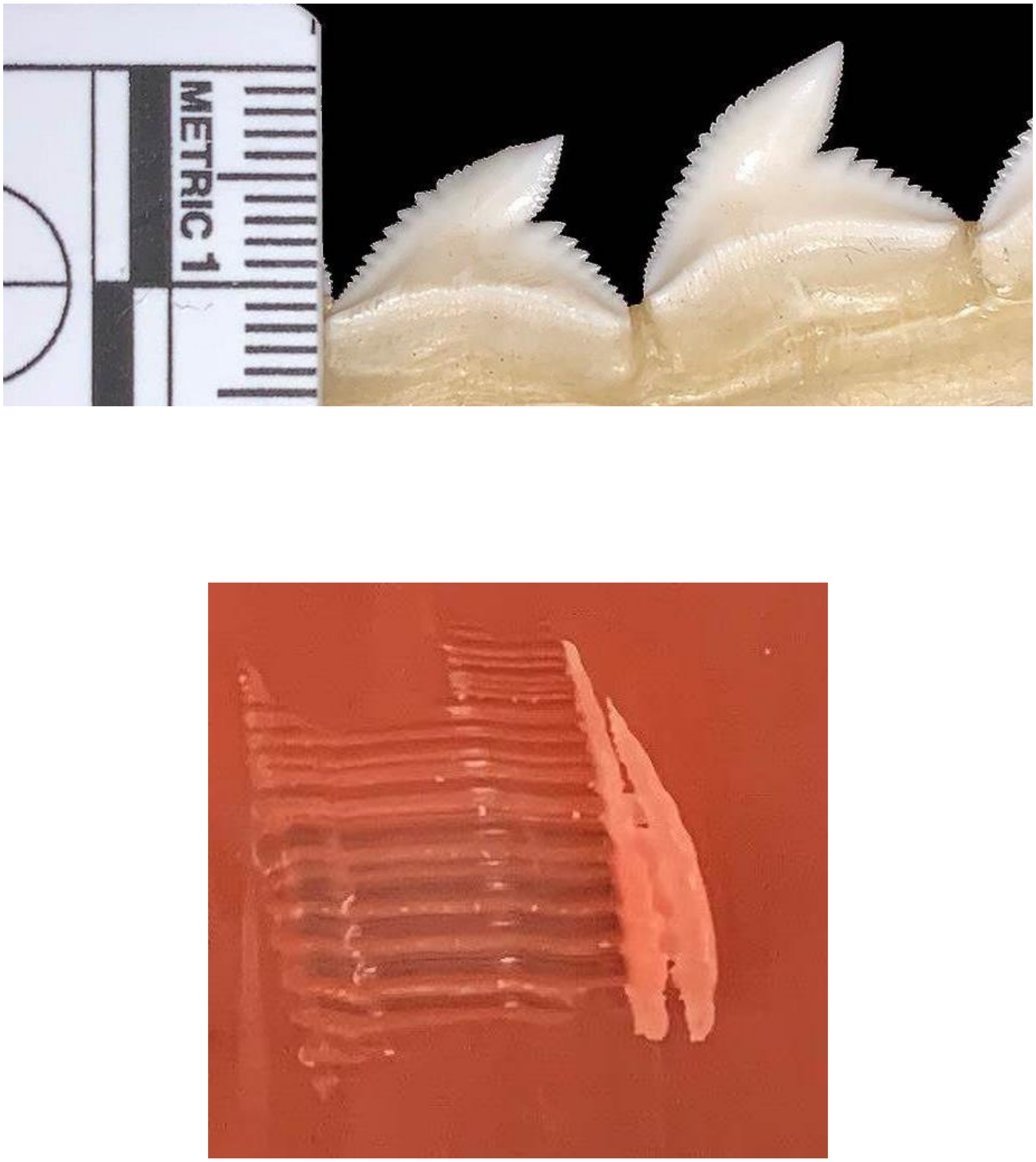

Figure 4.11. Classification of 2.5, tiger shark, (top image) individual tooth and (bottom image) striation pattern in wax.

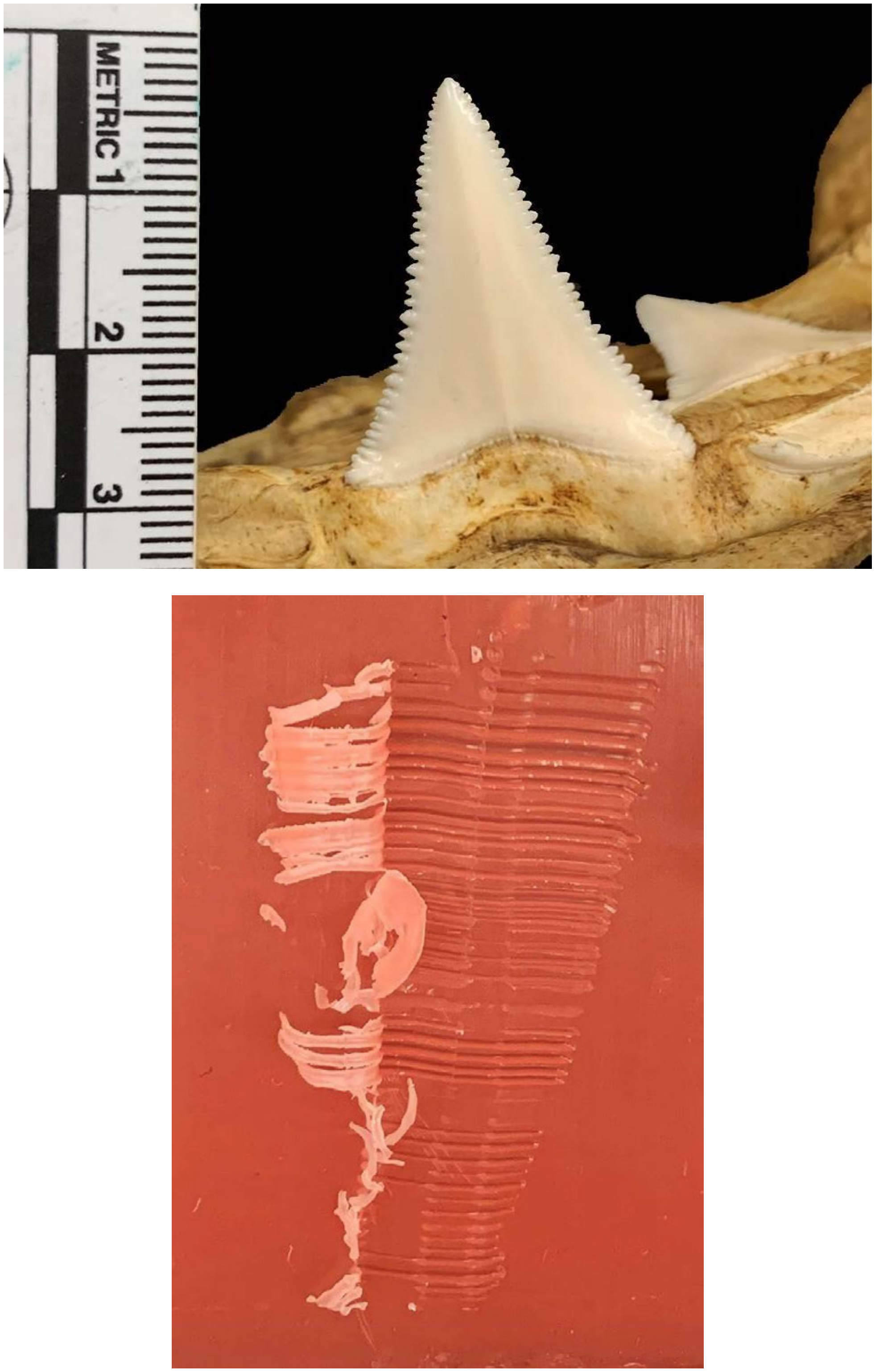

Figure 4.12. Classification of 3.0 and 3.5, white shark, (top image) individual tooth and (bottom image) striation pattern in wax.

To further determine the relationship between species and their pattern classification type, an independent samples Kruskal-Wallis tests was conducted to determine if striation height is distributed among species in the same way as pattern classification type (Table 4.12). With the significance level set at 0.05, the p-value for striation height was 0.000. This result means that the null hypothesis was rejected, and that the distribution of striation height among species is not the same across pattern classification types.

Table 4.12. Independent samples Kruskal-Wallis test for striation height across pattern classification type.

Test Statistic	Striation Height
Total N	145
Test Statistic	67.774[a]
Degree of Freedom	5
Asymptotic Sig (2-sided test)	0.000

a. The test statistic is adjusted for ties.

The pairwise comparisons were run between each individual for striation height, along with the adjusted significance from the Bonferroni post hoc tests (Table 4.13). The pattern types significantly different were: 2.5 and 3.0 and 2.5 and 3.5 (tiger/white), 0 and 3.0 and 3.5 (cookiecutter, tawny nurse, blue, blacktip reef, and sand tiger/white), 1.0 and

3.0 (blacktip reef, blue, bull, dusky, and java/white), and 1.5 and 3.0 (bull, dusky, gray reef, and java /white).

Table 4.13. Pairwise comparisons from the independent Kruskal-Wallis test of striation height and pattern type.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
2.5-.0	.321	15.809	.020	.984	1.000
2.5-1.0	15.386	10.365	1.484	.138	1.000
2.5-1.5	28.958	11.342	2.553	.011	.224
2.5-3.5	-71.121	20.648	-3.444	.001	.012
2.5-3.0	-86.589	12.397	-6.984	.000	.000
.0-1.0	-15.065	14.503	-1.039	.299	1.000
.0-1.5	-28.637	15.217	-1.882	.060	1.000
.0-3.5	-70.800	23.005	-3.078	.002	.044
.0-3.0	-86.268	16.019	-5.385	.000	.000
1.0-1.5	-13.572	9.437	-1.438	.150	1.000
1.0-3.5	-55.735	19.666	-2.834	.005	.097
1.0-3.0	-71.203	10.682	-6.665	.000	.000
1.5-3.5	-42.162	20.198	-2.087	.037	.774
1.5-3.0	-57.631	11.633	-4.954	.000	.000
3.5-3.0	15.468	20.809	.743	.457	1.000

Spearman’s rank-order correlations were also conducted for striation height against pattern classification type. This test was conducted in order to describe the relationship between the striation height left in the wax impressions and the pattern classification type (Table 4.14). The Spearman’s correlation coefficient, r_s, was 0.441 with a p-value of 0.000. This means that there was a moderate, positive correlation between striation height and pattern classification type, which was statistically significant.

Table 4.14. Spearman’s correlation of striation height with pattern classification type.

	Spearman’s rho	**Significance (2-tailed)**	**95% Confidence Intervals (2-tailed) LOWER**	**95% Confidence Intervals (2-tailed) UPPER**
Striation Height-Pattern Type	0.441	0.000	0.295	0.566

Tooth Dimensions by Species

Tooth dimensions by species was compiled into one table so each species can be compared to one another (Table 4.15). When compared to previous studies such as Nambiar et al. (1996) and Lowry et al. (2009), the species included in the present study are not unusual or outliers in their overall size. Size of the individual should be considered, as that growth is reflected in their teeth, serrations, and striations patterns.

Table 4.15. Tooth dimensions by species.

Species	Avg tooth height mm	Avg MD width mm	Avg striation height mm	BC Upper mm	BC Lower mm
Cookiecutter	8.1	4.2	X	78	97
Tawny Nurse	X	X	X	89	82
Sand Tiger	21.01	12.28	15.02	425	341
Lemon	12.95	12.78	X	368.5	315
Blacktip Reef	9.92	11.28	11.04	298	269
Blue	12.88	12.07	14.43	334	286
Dusky	8.32	8.13	10.47	303	273
Java	8.9	11.53	11.74	311	266.5
Gray Reef	9.88	13.24	13.36	344	317
Bull	13.08	17.25	14.17	444	387
Tiger	8.57	13.01	12.04	456	437
White	22.23	22.96	25.58	773	633

a. “X” indicates variable could not be measured.

DISCUSSION

Hypothesis Testing Results: Statistical Tests

Tooth Morphology

The hypothesis of this study stated that if the serrations and overall tooth morphology are distinct between species, then the striations will also be distinct. Therefore, the goal of the present study was to establish the fact that shark species do differ from each other in overall tooth morphology and in striation pattern, and that these variables could be quantified statistically.

The white shark is the most unique case across all species and all categories of analysis (height, MD width, upper and lower BC, and pattern type). They are markedly different from every other species. The tiger shark was also identifiable, especially when compared to the white shark. There were several unique species within this study group that had both serrated and nonserrated teeth within their dental arcs (blue and blacktip reef sharks), and individuals that only possessed nonserrated teeth (lemon, sand tiger, cookiecutter, and tawny nurse sharks). These species were included in the present study to understand and describe the type of pattern that their teeth leave behind, even if they are not the traditional striations that are characteristic of other species like the white, tiger, and bull sharks.

Potential for Species Identification

Based on the data provided by this study, future studies should be conducted in order for researchers to be capable of estimating species from striation marks and their patterns on bone. The white shark was the only species that could be consistently differentiated and identified through all types of analysis. White sharks have the longest and widest teeth, the largest BC for upper and lower jaws, and the largest, and most distinct striation pattern and impression. The dusky shark and the tiger shark were also able to be distinguished among the other species through all categories as well. The blacktip reef shark was unique in its BC for both upper and lower jaws and could be statistically differentiated from seven of the other 11 species. For the data that is available for the cookiecutter shark, they could also be identified apart from the rest of the group due to their unique dentition. The bull shark, while important due to its attack behavior, was not as easily identified or distinct from the other species, because their teeth are similar to a white shark, only scaled smaller in overall dimensions. There is potential that a bull shark tooth could be confused for a small-bodied or juvenile white shark.

Comparison with Other Studies

The bite circumference data obtained in the present study fit into the ranges provided by Lowry et al. (2009) for those species that overlap between the two studies (white shark, tiger shark, bull shark, dusky shark, and lemon shark) (Table 5.1). There were no species that did not follow the patterns that their study established, which means that the specimens used in the present study are not unusual or outliers for their species regarding their overall size and morphology. Thus, no individual from the present study should be excluded on the basis of being outliers of their species as have been described by other studies.

Table 5.1. Species' total length range and bite circumference range included in the present study (Lowry et al. 2009).

Species	Total Length Range (mm)	Bite Circumference Range (mm)
Carcharodon carcharias	1,245–5,632	Upper: 224-990 Lower: 180-760
Galeocerdo cuvier	711–3,581	Upper: 98-540 Lower: 97-532
Carcharhinus leucas	1,380–2,845	Upper: 199-443 Lower: 172-389
Carcharhinus obscurus	1,530–3,861	Upper: 212-465 Lower: 197-435
Negaprion brevirostris	685–2,680	Upper: 103-406 Lower: 93-389

The data provided in this study clearly distinguish white shark teeth and striation patterns, and tiger sharks to a lesser degree. Striation patterns could be used to help estimate species while also using the whole bite wound or any other item that get bitten during an attack, such as the victim's wetsuit or their surfboard. For any other potential species identification, the previous methods established in the field, especially the total body length estimate, the evaluation of the individual teeth left in a would, and their impact should be utilized.

The capability to identify down to the species level was first proposed because there are enough differences seen between species in their tooth morphology; there is a uniqueness of dentition across the species that were examined (Whitenack and Motta 2010). Even the individuals that were categorized into the same group of striation pattern as another species, differed in their overall tooth morphology and dental arch composition. For example, both the blue shark and the blacktip reef shark had mixed pattern types in their overall dentition and were placed in the same group, but their teeth reveal that the blue shark has a much more pronounced curve in their upper teeth. In this, different tooth morphologies of the species affected the ability to obtain their impression. However, statistical analysis only reflected sone significant results for those species with unique tooth morphology. The tiger and blue shark had statistically significant results that differentiated them from the white shark in striation height and pattern type, but this is not unexpected as the white shark was distinguished from almost every species for at least one analysis.

This does not mean that the significance of striation patterns should not be considered when discussing shark teeth and their impact on objects and people. Previous studies have noted the striation pattern that gets left behind in the form of either light or deep striations on the surface of the cortical bone, but there have not been any studies that have attempted to analyze the striation patterns (Allaire et al. 2012). Nambiar et al. (1996) examined white shark teeth and specifically at the pattern of their serrations; however, they were attempting to place a singular tooth within an individual’s entire dental arch, which proved to be difficult. Separating a species from one another by serration and striation pattern rather than one tooth in an entirely similar dental arch was just as difficult.

Other Factors That May Affect Species Identification

As addressed above, this study utilized dental wax to capture the impressions from the teeth. This material gave the clearest impression and was formulated for the use on teeth. The wax was malleable and easy to work with. However, because of its softness and malleability, it was likely not the best allegory for bone, and how the striations would appear on human bone. This may have an effect on future identification of species based on striation pattern. It is not likely that the overall pattern of a serration or striation would be different and incomparable to the data provided by this study, but it is a consideration.

Another factor that potentially could impact correct species assessment is that fact that sharks are homodont, meaning that they have the same type or class of tooth across their jaws. Some may classify blue sharks and blacktip reef sharks as heterodont, since they have a jaw comprised of serrated and nonserrated teeth. It can be more difficult to determine the cause of the type of animal or species when they are homodont, because the analysis cannot be based on the overall dental formula that are found on an impression (Nambiar et al 1996). Other species that have successfully been studied based on dental impressions are heterodont, including humans (Pokines 2022). If there are varying number of incisors, canines, premolars, and molars, the identification of the species in question is already narrowed down to a select number of individuals, whereas sharks and other homodont species, such as alligators, do not have the same identifying dentition.

Shark species that do not have serrations on their teeth such as species of mako, and in this study, the sand tiger shark and the lemon shark, and those species with mixed dentition of serrated teeth and nonserrated teeth such as blue sharks, can have an effect on the striations left behind and their classification. Those that had mixed dentition were classified based on their serrated teeth. It is not improbable to question if analysts could confuse a predation event of one shark, such as a blue or black tip reef shark, with a large scavenging event of more than one species based on striations of a serrated tooth being present along with the sharp force trauma more expected of a mako-type species that occur with nonserrated teeth.

Increasing Attacks, Climate Change, and Human Reactions

Climate Change and Shark Attacks

Shark attacks are increasing throughout the world for a variety of reasons, including the fact that the human population is ever increasing, which leads to more people being in the water than ever before (Chapman and McPhee 2016; West 2003). Because of this, the number of outdoor recreational activities has also increased, leading to an increased risk of humans and sharks encountering one another, and increasingly the likelihood of that interaction becoming dangerous. Because of this probability, there is then a need to identify victims in the case of those found at sea, the remains that wash up on shore, and the need to identify the shark species involved in any attack or interaction. Improved forensic techniques could provide much of the necessary information in many of these cases.

Climate change is also changing the pattern at which humans and sharks are interacting with one another (Birkmanis et al. 2020; Chin et al. 2010; O’Brien et al.

2013). The global oceans are absorbing around ninety percent of the heat that has been trapped in the atmosphere due to anthropogenic causes such as greenhouse gases, which is raising ocean temperature around the world (Birkmanis et al. 2020; Chin et al. 2010). Rising ocean temperatures are expanding the geographic distributions of numerous shark species, that favor temperate to tropical water temperatures like the tiger shark. This is leading to these species getting closer to shorelines and into the areas that people are most likely to frequent. In the case of Australia, and likely other places around the globe, the types of sharks that can be found in one zone of the ocean are changing. Within the Australian continental Exclusive Economic Zone (EEZ), over the next several decades, shark habitats will shift, causing the types of sharks that can be found in this zone to also shift. Likely, the habitats preferred for requiem sharks, those that can be found in the family of Carcharhinidae such as the bull shark, tiger shark, blacktip reef shark, and many other will decrease, and those preferred by the white shark, will increase (Birkmanis et al. 2020). These shifting zones and habitats could have an untold impact on human-shark interactions in the future and knowing these shifts would aid efforts to reduce the number of human-shark interactions that are occurring at increasing amounts every year.

The climate change that the earth is currently experiencing is also more extreme than anything that has been seen in recent history, and its effect on the marine ecosystems has yet to be fully realized. Most periods of climate change that have effect marine life have been a decrease in temperature, lower sea levels, and glacial advances, not an increase in temperature and sea levels like what is being seen now (O’Brien et al. 2013).

Sharks, especially those that live in deep water, have thus far not been affected much by climate change, as ocean temperatures at their depth do not change as much as those on the coasts and near the surface (O'Brien et al. 2013). In the past, when water temperatures have dropped, the species that inhabit the coasts and near the surface were more affected because their habitat shrunk, leading to decreased population. With the reversal of the water temperature and sea levels occurring now, sharks where depth is their usual habitat are more at risk, because the species living closer to the surface will now have an expanded habitat to the deep species' detriment. These species may experience population bottlenecks and range constrictions. Because the ocean is warming, and the temperatures, especially at the surface are increasing at such a rapid rate, the predictable changes that have been seen previously are now not so predictable (O'Brien et al. 2013). It is not well researched how different shark species will respond to the increasingly warmer ocean waters. It may be an unintentional side effect of anthropogenic activities that brings sharks and humans in more contact.

Overfishing and Overreacting

Because shark attacks and human-shark interactions are increasing every year, there is a very real fear among people of sharks (Ostrovski et al. 2021). For this reason and the fact that shark fins are sought to be eaten, sharks are at an increased risk of overfishing. As stated above, the top three species involved in attacks on humans are vulnerable and near threatened status, which has resulted in a need for conservation. Like any apex predator, they help maintain a balance within their ecosystem, and overfishing could have detrimental defects for marine health. Because of this, there is an intense push for the conservation of shark species, and there have been several methods employed (Hazin and Afonso 2014; Ostrovski et al. 2021; Stevens et al. 2000). Also, despite the reported fear of sharks, the public, on average, supports the need for their conservation, as they recognize that sharks are in their natural habitat, and it is humans that are infringing on their territory when attacks occur (Ostrovski et al. 2021).

In Brazil, Hazin and Afonso (2014) reported on a green strategy of trying to limit the number of shark attacks that occurred in its waters while conserving the species there by preventing the killing of these sharks. Previously, the prevention of attacks by dangerous species were mitigated using gillnets, which often killed those animals that got trapped. Unfortunately, this was not limited to their targets of dangerous and aggressive sharks, but it also included whales, dolphins, sea cows, and turtles, many of whom include endangered or otherwise protected species (Hazin and Afonso 2014). Because of the many negative effects, a new program had to be installed. The focus of this new program where those species that were deemed aggressive, those like bull shark and tiger sharks, were targeted for these actions. The program that launched this initiative is called the Shark Monitoring Program of Recife (SMPR). The sharks that were caught using this new program were rereleased away from shore, and therefore away from people. This decreased the number of shark attacks in the region, while also preventing the unnecessary killing of shark and aiding in the conservation efforts of these species.

Overfishing in response to shark attacks is also extremely detrimental to shark populations. The fear that people have for sharks is not always rational, and people have reacted negatively in the past. Large animals, like sharks, as well as dolphins and whales often have lower reproductive rates than the fish that are generally targeted by fisheries. When these animals are caught and killed, it can have a huge impact on the species overall due to this low reproductive rate; they cannot replace the individuals lost fast enough to keep the overall population levels stable. While purposeful overfishing of sharks is damaging to the species' numbers, those that are taken as by-catch are a bigger problem. This is because those that are caught and killed as by-catch are not required to be counted and therefore, it is not managed (Stevens et al. 2000). This creates an unknown number of individuals that are killed yearly from this practice, making tracking population numbers even harder than before. Overfishing does not just affect the species that are being overfished; since sharks are at a high trophic level, removing large numbers of their populations can have unforeseen effects on the marine ecosystem as a whole. In the study conducted by Stevens et al. (2000), the Venezuelan shelf ecosystem could see dramatic changes in the abundance of species found inhabiting those waters. In this specific region, those that only contribute slightly to the shark diet would boom in their numbers, others like some species of squid would decrease right along the shark population. The Hawaiian coral reef model responded quite differently than the Venezuelan shelf, which further proves that shark populations have a complex effect on different ecosystems and the depletion of their populations could cause unpredictable changes in the oceans (Stevens et al. 2000).

CONCLUSIONS

Utility of Striation Patterns in Identifying to the Species Level in Sharks

The current study has examined the teeth and striation patterns of 158 impressions across 12 different species of shark. Given the results, it can be tentatively concluded that white sharks and tiger sharks can be identified based on the striation patterns that their teeth can leave behind on bone during an attack or scavenging event. While the utilization of other factors such as location of the attack and known shark geographic distribution, location of the bite wound, and bitemark circumference found from damage on the victim's belongings should still be common practice, the striation patterns are also unique and could provide the extra information. For example, in the case from Stock et al. (2017) where the species was narrowed down to a bull and a tiger shark, due to the present analysis of data, the two types of striations are different and could likely point to one species over the other for the most likely candidate that was involved in that predation event.

The methods used currently in determining the likely species are all useful, and they can often narrow the field to two or three species that could be involved. The intent for this study was to find a method that could take those few species and compare them against known patterns of injury of teeth on another surface to identify the most likely individual to be involved in the attack. Therefore, the utility of using striation patterns in identifying the species responsible is possible; however, more research with different methods is needed. There are many ways that this research can grow in the future to make this a robust method for identifying species of sharks in different attacks and other predation events that can occur on humans.

Forensic Application

While the methods previously established are the standard to use when pathological and forensic evidence is evaluated from a shark attack, many of these methods have only focused on one species at a time or on solely estimating the total length of the individual shark that appropriated an attack, of which there is significant overlap between species. This provides a list of species that could be involved, but often one species cannot be identified.

Many cases of remains that involve shark predation events have washed up on shore or remains from inside of sharks, cases in which forensic anthropologists were required to assist in order to understand the damage done to these remains (İşcan and McCabe 1995; Stock et al. 2017). These remains were also often only partial remains, and they were also mostly skeletonized, prompting a forensic investigation. The research conducted in this study is also especially relevant to the field, as there is a smaller subfield of study within forensic anthropology, taphonomy, that must be studied and understood by practicing forensic anthropologists. This subfield is used to determine what happened to human remains and in what order they occurred. Carnivore predation and behavior is a large portion of this subfield, and for most of the lifespan of this subfield, the focus has remained on terrestrial carnivores (Pokines and Higgs 2022; Pokines 2022). Marine carnivores, as observed, can cause just as much damage, and disperse remains, the same way that terrestrial carnivores can and do, therefore, marine carnivore damage should also be as thoroughly researched.

Limitations

Shark teeth specimens were difficult to obtain, and those that are represented in the Harvard Museum of Comparative Zoology and the Shark Reef Aquarium collections, especially the more infamous species of the white, tiger, and bull sharks, were not easily accessible. Commercial purchase of shark teeth was an option; however, the most important species being observed were the most expensive, and therefore unable to be included. Large, individual white shark teeth could be several hundred dollars each. These three species are also considered to be vulnerable and near threatened on the IUCN Red List, which raised ethical concerns of purchasing shark teeth without knowing if they were collected passively or caught and killed for profit (Midway et al. 2019).

Future Research

One important area which can be expanded upon for future research is the utilization of larger sample sizes. COVID restrictions were extremely tight and difficult to work around for the duration of this study, and as such, the sample size of specimens is lower than if more institutions with large collections could be accessed, as well as longer periods of times at the institutions that were able to be accessed and utilized. Only two full jaw samples from each of white sharks, tiger sharks, and bull sharks were able to be used, which should be a higher number, although it did follow previous trends as

Nambiar et al. (1996) only had access to three white shark specimens for their study. As such, these are the species that are most often involved in human-shark interactions and are also often the deadliest interactions. With their geographic distribution being similar now that shark behavior is changing due to global warming, being able correctly to identify the species involved in an attack will be beneficial. It will also prevent unnecessary loss of life if the wrong species is tracked and killed for an attack.

While this project included 12 different species of sharks, there are many more than come into contact with humans, even if the interactions are not as deadly as those when encountering white, tiger, and bull sharks. Mako sharks, oceanic whitetip sharks, and blacktip sharks are all recorded as coming into significant contact with humans (Chapman and McPhee 2016; Levine et al. 2014). Blacktip and spinner sharks are also often the species that the less than deadly attacks can be attributed to (Lentz et al. 2010; Stock et al. 2017). These species were either unavailable for study, or the time constraint made it so they could not be documented. In the future, the addition of these species to the reference guide would be highly advisable.

In the future, the utilization of bone, either animal or human, should be used in place of the dental wax exhibited in this study. This is so that there is a closer approximation to how bone would react when shark teeth come into contact with it, which would provide an overall more accurate picture of the damage caused. Dental wax was the best option for this study due to concerns from the institutions that housed the specimens used, as well as the fact that the dental wax was able to provide the clearest impression. In the examination of striations on bone from an attack or scavenging event, impressions this clean may not occur; however, it is a launching point for researchers to use to understand the differing patterns that can be seen. Now that this has been accomplished, creating impressions on a harder medium is advised. It could also be an interesting study to include different textures that could be found with victims of shark attacks, such as surfboards and wetsuits as these are often items that incur tooth damage incidentally during an attack or other predation event. The utilization of different analysis methods, using more advanced statistics or programs such as Elliptical Fourier Analysis could also be included in future research.

With the data in the present study, it can be concluded that only the white shark and, to a lesser ability, the tiger shark are distinct in their tooth and striation morphology. The use of striations and their patterns is still relatively unknown, with only two species that could possibly be identified among the 12 species in this study and the many species yet to be analyzed. With more avenues of research identified and available, the use of striations to identify a species involved in an attack may become a method employed by scientists in the future.

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