# A comparison of alternative systems to catch and kill for mitigating unprovoked shark bite on bathers or surfers at ocean beaches

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## Abstract

Responses to unprovoked shark bite involve public policies and management approaches that contend with the needs of public safety and the responsibility to protect threatened species. In Australia (Queensland and New South Wales) and South Africa, methods that aim to capture and kill large sharks adjacent to popular beaches are a long-standing approach aimed at reducing the risk of shark bite. This paper reviews non-lethal alternatives to catch and kill methods , and suggests optimal conditions for non-lethal systems that will assist policy makers and beach authorities in choosing public safety responses that can be applied at the ocean beach scale. Deployment needs to be strategic with sufficient knowledge of their likely effectiveness under local conditions. At this stage we believe there is no single approach universally applicable to ocean beaches where unprovoked shark bite occurs, although well considered and locally appropriate can reduce risk. .

**Keywords**: unprovoked shark bite, shark attack, mitigation, ocean beaches, surfing, bathing.

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## 1. Introduction

Unprovoked shark bite represents a complex challenge for managers, scientists, policymakers, conservationists and water users (McPhee, 2014; Gibbs and Warren, 2015; Gray and Gray, 2017). Globally, the frequency of unprovoked shark bite has been increasing (McPhee, 2014). Whilst an increase in the number of water users over time contributes to this trend, it does not explain it entirely (Chapman and McPhee, 2016). Environmental factors which influence shark distribution and behavior such as ocean temperatures, the distribution and abundance of prey, and habitat changes are potential influences (Amin et al, 2012; McPhee, 2014; Chapman and McPhee, 2016; Lagabrielle et al., 2018; Lee et al., 2018; Ryan et al., 2019). While the probability of an unprovoked shark bite remains low, the vivid nature of a shark bite ensures a high degree of media reporting and public concern (Neff, 2012; McPhee, 2014; Simmons and Mehmet, 2018).

Responses to unprovoked shark bite involve public policies and management approaches that contend with the needs of public safety and the responsibility to protect threatened species (McPhee, 2014; Pepin-Neff and Wynter, 2018). Management agencies may implement measures that attempt to reduce bite risk, address public concern, or provide warning systems to identify the presence of sharks at a beach in real-time. In two Australian states (Queensland and New South Wales) and South Africa, methods that use fishing apparatus to capture and kill large sharks adjacent to popular beaches are a long-standing approach aimed at reducing the probability of an unprovoked shark bite (Cliff and Dudley, 1992; Sumpton et al., 2011). Two types of fishing apparatus are used – mesh nets or drumlines (**Figure 1**). These two measures have become highly controversial (Meeuwig and Ferreira, 2014; Gibbs and Warren, 2015; Simmons and Mehmet, 2018; Gibbs et al., 2020) due to a realisation of the low risk to humans posed by most sharks, the conservation status of some shark species, the role of many sharks as apex predators, the recognition of the need to reduce the overall anthropogenic mortality on shark species from various sources, and changes in public perception towards the intrinsic value and ecosystem benefits of sharks (Simpfendorfer et al., 2011; O'Connell and deJonge, 2014; Gibbs and Warren, 2015; Pepin-Neff and Wynter, 2018). It is also due to the bycatch captured using these methods (including marine turtles and marine mammals), despite the efforts to reduce it through gear modifications and timing of deployment (Dudley and Cliff, 2010; Sumpton et al., 2011). There is a recognised need to use non-lethal methods including new technologies that provide for enhanced safety and peace-of-mind for beach users, while reducing or eliminating significant environmental impact (Meeuwig and Ferreira, 2014; Gray and Gray, 2017; Simmons and Mehmet, 2018). This need is principally focused at ocean beaches where there are many water users (particularly bathers and surfers), although the issue can extend to other marine habitats (e.g. reefs, estuaries and rivers).

There has been much research and focus on individual deterrents that an individual may use to deter a shark or reduce the risk of a bite occurring (Sisneros and Nelson, 2001; Smit and Peddemors, 2003; Stroud et al., 2014; Hart and Collin, 2015; Huveneers et al., 2018a and b; Egeberg et al., 2019; Thiele et al., 2020). However, for a management agency needing to enact public safety responses to the risk of unprovoked shark bite, the focus is not on approaches that an individual can use, but rather those that can be applied over a wide area (e.g. at a whole or a large section of beach). This paper reviews relevant alternative non-lethal approaches to currently used lethal fishing apparatus (mesh nets and drum lines) through consolidation of publications and reports from diverse and often difficult-to-source records and discusses their utility under various scenarios and conditions in a format that will assist managers and decision makers in choosing area-based public safety responses that can be applied at ocean beaches under diverse conditions.

## 2. Occurrence of Potentially Dangerous Sharks and Consideration of Local Conditions.

Three species of sharks (white sharks *Carcharodon Carcharias*, tiger sharks *Galeocerdo cuvier*, and bull sharks *Carcharhinus leucas*) have been implicated most in unprovoked shark bite (McPhee, 2014). An understanding of any seasonal occurrence, physiology, behaviour and preferred diet is important in adopting an appropriate management strategy to minimise risks to bathers or surfers. For example, it may be prudent to consider that the risk of encounters by water users with bull sharks may be increased in summer periods following heavy rainfall and highly turbid waters (Werry et al., 2018).

Managers should also be aware of biophysical factors associated with local bathing or surfing areas that may increase the risk of a bite. Examples include proximity of bathing or surfing areas to deeper channels, estuary mouths or anthropogenic discharges (Blaison et al., 2015; Ryan et al., 2019); fishing activities (Lippman, 2018); and high abundance of marine mammals and/or the occurrence of marine mammals that are washed-up dead or stranded on beaches (Spirivulus, 2014; Chapman and McPhee, 2016; Lippmann, 2018). If the risk of occurrence of dangerous sharks is abnormally high, managers may need to implement increased public protection measures, including initiating or upgrading some of those discussed, or even implementing temporary closure of the area to water users. Collecting and utilising this information in a systematic way can contribute to mitigation by identifying factors that may enhance risk at the local level and then using this information in educational material.

## 3. Overview of the Alternative Approaches.

Non-lethal approaches for protecting humans from potential shark bite can be divided into two main categories: ‘detection’ of potentially dangerous sharks; and ‘deterring’ them from bathers.

Shark detection can include methods that: a) use aerial views over the beach, through an aircraft (manned fixed wing or helicopter (e.g. Robbins et al., 2014), or unmanned aerial vehicles (e.g. Colefax et al., 2019; Butcher et al., 2020) or balloon ( Kiszka and Heithaus, 2018)) or personnel on land to detect and identify a potentially dangerous shark (Oelofse and Kamp, 2006; Kock et al., 2012), b) are in-situ and aim to detect a previously tagged shark (e.g. Hazin et al., 2013; Bradford et al., 2011), and c) are in-situ and aim to detect all sharks (tagged and untagged) within a defined area (e.g. Parsons et al., 2014). To be effective as a direct protection method, information regarding the presence of a large shark needs to be communicated to water users in real time (Bradford et al., 2011).

Deterring sharks involves providing stimuli to a shark which results in a high probability of a shark not moving into a beach environment where water users are present or excluding them altogether. Shark deterrents can utilise physical barriers, or electro-magnetic fields or visual, auditory or chemical stimuli, and such approaches are based on an understanding of the sensory biology of sharks (Hart and Collin, 2015). Physical barriers (permanent or temporary) are purpose-built barriers that do not aim to catch sharks, but rather exclude sharks from an area where water users are present and thus create an environment where people can participate in water activities where sharks are absent (O’Connell et al., 2018).

### 3.1 Detecting Sharks – Aerial Surveys and Land based Approaches.

Aerial surveys have been used to assess abundance and distribution of several shark species (Wilson, 2004; Cliff et al. 2007; Rowat et al., 2009; Dicken and Booth, 2013; Kaijura and Tellman, 2016). Variables that limit the effectiveness of the aerial surveys include water clarity, wind strength, sea chop, water depth and the behavior of the shark species themselves (Robbins et al., 2014; Colefax et al., 2018; Butcher et al., 2019). In the context of beach protection, these limitations can, result in inaccurate assessment of risk to beach users. They are also relevant variables to consider for land-based approaches (Engelbrecht et al., 2017).

*Manned aerial surveys:*

A single manned aircraft allows a large area of coastline to be surveyed, but only a limited amount of survey time at a single location. Manned aircraft travelling along a coastline spend a very small amount of time over each beach (often less than a minute) as, depending on stalling speed of the aircraft, they are inevitably flying at over 70km.hr$^{-1}$ (Rowat et al., 2009) and thus limit the opportunity to locate a shark present off a given beach.

Robbins et al. (2014) specifically assessed the efficacy of manned aerial surveys (helicopter and fixed wing aircraft) to detect sharks for beach safety by deploying and trying to detect shark analogues. Even with good water clarity (approx. 6 m), observers in fixed-wing or helicopters could detect the shark analogues only if they were shallower than 2.5 m and 2.7 m below the water surface, respectively. During subsequent work with analogues placed less than 2.5 m underwater, observers still recorded sightings very infrequently, with overall sighting rates of only 12.5% and 17.1% for fixed-wing and helicopter observers, respectively. Although helicopter observers had consistently higher success rates of sighting analogues within 250 m of their flight path, neither aircraft observers sighted more than 9% of analogues deployed over 300 m from their flight paths. Overall, the low rates of detections found by Robbins et al. (2014) led them to express serious doubts on the efficacy of manned aerial beach patrols (using human observers) as an effective early-warning system to prevent shark bites.

*Unmanned aerial surveys*:

Unmanned Aerial Vehicles (UAVs, also known as 'drones') cost less to operate than manned aircraft, are more suitable than manned aircraft for surveying a single location but commercially available models are currently still limited in their air-time due to battery constraints. Several marine fauna studies have been published using UAVs (Koski et al., 2009; Hodgson et al., 2013; Colefax et al., 2017, 2019; Kelaher et al., 2019). For beach safety, Butcher et al. (2020) conclude that a dedicated observer, in addition to a drone pilot, significantly improves detection probability and reduces delays in sending warnings. Development of algorithms to automate accurate detection of potentially dangerous species in real time are possible (Sharma et al., 2018; Colefax et al., 2019; Gorkin et al., 2020), but surface chop and water clarity could still prove too complex to be reliable under the variable conditions usually experienced within one day at a beach. Kelaher et al. (2020) indicated comparable precision in real-time detection of marine fauna between helicopters and UAVs, although post-hoc analysis of video footage taken by the drone led to higher accuracy. Although, civil aviation restrictions in many countries will limit the use of UAVs for surveys covering long distances, they will likely fill a niche for surveying over small distances. The use of tethered UAVs via helium filled balloons and/or kites may provide opportunity for longer-term surveillance beyond what is possible for remotely piloted UAVs (Kiszka and Heithaus, 2018).

Emerging UAV technology may address some of the limitations of using people to detect sharks reliably. Multispectral imaging shows promise as a remote sensing tool in the marine environment (Chirayath and Earle, 2016) and has been trialed as a method for detecting sharks. Using shark analogues, Lopez et al. (2014) found detection rates averaging 84.8% when multispectral imaging was used, a substantial improvement on the estimates obtained by Robbins et al. (2014). Further testing of multi-spectral approaches is required on actual sharks rather than shark analogues and over a range of conditions including conditions present along ocean beaches.

*Land-based shark spotter programs*:

Those responsible for general surf safety at beaches (e.g. surf life savers) may also contribute to mitigating the risk of unprovoked shark bite by keeping watch for large sharks, alerting water users when sharks are present, and directing them out of the water. In the early 1900s several Australian beaches erected shark spotting towers to assist life savers to protect bathers from shark interactions (Neff, 2012). Towers are still used in several locations globally, as these may improve detection by increasing the range over which a shark can be spotted. However, for land-based spotting to be effective, vantage points with substantial elevation are required (> 40 m above sea level) (Kock et al., 2012). This height is well above that normally afforded by surf patrol towers, but observers on suitable headlands may provide coverage suitable for shark detection. The South African 'Shark Spotters' program developed and trialed in Cape Town in response to a series of unprovoked shark bites utilizes such local mountain lookouts for their teams of shark spotters (Oelofse and Kamp 2006). The program is an early warning initiative that provides information in real time on the presence or absence of dangerous shark species to beach goers (Engelbrecht et al., 2017).

The program is effective only when spotters are in place (0800 to 1800 in South Africa). While sea state and weather condition affect the likelihood of sighting a shark, this limitation can be incorporated into the warning system, as per the black flag used in South Africa to denote when spotting conditions are poor (Engelbrecht et al., 2017). Additionally, the aspect of the beach relative to the sun influences glare. At beaches which face east or west, glare from the sun may reduce the reliability of spotting in the mornings or afternoons, respectively. Further, the issue of fatigue of observers needs to be managed. These factors affecting the ability of dedicated spotters to sight sharks have not been scientifically tested and require independent determination of shark presence through, for example, aerial confirmation or acoustic tracking of tagged sharks through the area.

### 3.2 Detecting Sharks – Tagged Animals.

Telemetry projects on sharks occur world-wide (e.g. Hammerschlag et al., 2011; Hussey et al., 2015), but their project design has seldom focused specifically on shark bite mitigation (McAuley et al., 2016). Potentially dangerous sharks can undertake large scale movements which cover numerous habitats and nearshore conditions (Bruce et al., 2006; Heithaus et al., 2007; Heupel et al., 2015). Telemetry studies on bull, tiger and white sharks have yielded information on their movements and patterns of habitat use in coastal waters which is relevant to bather safety (Blaison et al., 2015; McAuley et al., 2016; Smoothey et al., 2019; Niella et al., 2020). However, in order to provide information on tagged shark presence to beach users any telemetry array would need to be at a fine scale and deployed to ensure tagged sharks have maximum likelihood of being detected (McAuley et al., 2016). Engelbrecht et al. (2017) and Kock et al. (2018) demonstrated that such studies over time can provide significant information which identifies areas and times where overlap between sharks and humans is elevated.

Acoustically-tagged sharks can be detected by arrays of fixed receivers that either log the presence of the tagged shark for future download by the receiver owners or send the record in near-real time to the owner (Bradford et al., 2011). Alerts for tagged sharks of relevant species can then be communicated to the public via social media, dedicated websites and text messages to subscribers. However, managing public fear is potentially complex when using these real-time listening stations as the sharks may be detected 1km off the beach (assuming a 500m detection radius and the station being deployed 500m off the beach), in which case they pose no risk to beach users, yet they are alerted to the presence of these offshore sharks.

The more tagged sharks of relevant species that are utilising coastal areas the greater the likelihood of a detection at a beach where a receiver is present. Maintaining receivers in position requires mooring designs informed by knowledge of longshore sand movement and regularity of scouring events, plus oceanographic conditions and severe weather events potentially encountered in the region. Placement of receivers should be such that they provide the detection swath relevant to the local site. Studies have been conducted to determine effective range of detection for acoustic tags under varying environmental conditions (Kessel et al., 2015; Huveneers et al., 2016), a critical factor to consider when designing an acoustic receiver array for protection against unprovoked shark bite. As well as maintaining these receivers in place, an ongoing shark tagging program is required as new cohorts of sharks of a size potentially capable of biting a human will annually recruit into the population and may be present along coastlines. These factors subsequently can lead to an expensive ongoing shark tagging program for the management agency responsible for beach safety. In many cases, the cost is likely to be prohibitive for many management agencies, particularly in developing countries. Where possible, partnerships between management agencies at different levels of government and relevant institutions can share the cost burden and provide large-scale assessment of animal movements such as those achieved through national programs e.g. the Integrated Marine Observation System Animal Tracking Program in Australia (Harcourt et al., 2019), or through more localized species-specific collaborations such as the Shark Monitoring Network in Western Australia which involves Commonwealth and State government agencies, Australian universities and international support (McAuley et al., 2016).

### 3.3 Detecting Sharks – Untagged Animals.

Untagged sharks may be detected by in-water observers (divers), capturing the 'image' of a shark via camera deployments, sonar technologies, or capturing sharks using fishing techniques. In Reunion, divers enter the water and patrol the area (Lagabrielle et al., 2018). This approach is labour intensive, carries a safety risk to the divers and relies on suitable water clarity and sea state to be effective. Similarly, monitoring shark activity using underwater cameras relies on suitable water clarity; although, the advent of cost-effective wireless data transfer could allow cameras to stream video to land-based stations where observers or computer algorithms would confirm shark presence.

Sonar arrays have potential to detect sharks without the need for sighting or capture. Sonar technologies have advanced substantially in recent years and may have potential for shark bite mitigation. Parsons et al. (2014) identified that for a given frequency and noise level, maximum detection and identification ranges are influenced by system source level, beam pattern, bathymetry, object target size and acoustic reflectivity. For the deployment of a vertical array of sonar units to cover an area, they identified the importance of interference where beams from more than one-unit overlap. They concluded that a vertical array in shallow waters (< 15 m) may be unsuitable at ranges exceeding 75 m.

The surf zone is a more challenging environment than that assessed by Parsons et al. (2014) in terms of the effective range of a sonar unit. Acoustic propagation in the surf zone is a difficult and challenging problem in underwater acoustics (Farmer et al., 2001; Vagle et al., 2005). As sonar units are expensive, the number of units potentially needed to provide detection at a beach is an important consideration in terms of the cost effectiveness of the technology if applied in practice. Overall, the efficacy of sonar to detect sharks for the purpose of beach safety is not yet adequately proven.

A final method of detecting presence of potentially dangerous sharks is via their capture using fishing gear. The capture and release of sharks can result in physiological stress for the animals and potential mortality (Skomal et al., 2007; Marshall et al., 2012, 2015). Capture by fishing gear is clearly not always a non-lethal method, but technological and operational improvements have resulted in the release of captured sharks with improved survivorship. The South African and New South Wales shark bite mitigation programs release all live sharks, but high mortality rates occur (> 80%) for large 'target' sharks caught in the nets (Cliff and Dudley, 2011; Dalton et al., 2017). Survivorship on traditional drumlines in Queensland were 25.9% for bull sharks, 31% for tiger sharks, and 47.4% for white sharks (Sumpton et al., 2011). The first 'green strategy' for mitigation of shark bites was initiated off Recife, Brazil, using longlines and drumlines to catch sharks for relocation offshore in waters more than 25 m deep. Survivorship rates for tiger and bull sharks in these hook-based fisheries were 82.4% and 50%, respectively, but no differentiation is provided for longline versus traditional drumline mortality rates (Hazin and Afonso, 2014). Gallagher et al. (2014) also found that survivorship was higher for tiger sharks compared to white sharks.

Recently, a new shark fishing device known as the Shark-Management-Alert-in-Real-Time (SMART) drumline was invented to maximise survival rate of captured animals (Guyomard et al., 2019). SMART drumlines include a GPS satellite buoy and a 'Catch-A-Live'™ system alerting fishers when an animal is caught in near-real time. The alert is initiated when the bait is taken by an animal and the magnetic trigger is activated. The approach constitutes a meaningful compromise between the need to target potentially dangerous species near popular beaches and the requirement to safely release, and possibly tag captured animals (Guyomard et al., 2019). They also provide an opportunity to translocate and release offshore any captured shark, as has been initiated in Brazil (Hazin and Afonso, 2014). Guyomard et al. (2019) found that 86.9% of animals could be retrieved alive, however, the survival rate varied among species ranging from 94 - 96% for bull and tiger sharks to approximately 46% for scalloped hammerheads (*Sphyrna lewini*). Similar high levels of live shark releases have been reported over 3 years of SMART drumline trials in NSW, with 404 white sharks (1 dead), 83 tiger sharks (all alive), 11 bull sharks (all alive) and 212 non-target animals (5 dead) caught (NSW DPI, 2019). In Western Australia, a year-long trial of SMART drumlines resulted in the capture of 148 sharks and rays with 88% being released in good condition and no recorded mortalities of any shark species (DPIRD, 2020). The Western Australia trial only resulted in the capture of two white sharks and this low level of capture compared to New South Wales which was attributed to differing operational environments, different populations of white sharks, and the fact that several SMART drumline deployments in New South Wales occurred in known white shark nursery areas (DPIRD, 2020). Reducing animal mortality requires extra labour expense, due to standby requirements for rapid response to a capture. Subsequent analysis of environmental factors associated with captures may lead to understanding conditions affecting shark abundance and distribution in nearshore waters which can further inform mitigation strategies. Guyomard et al. (2020) investigated whether the use of baits on SMART drumlines attracted sharks closer to water users but demonstrated that it was not the case.

### 3.4 Area-Based Deterrents.

Sharks have specialised receptors (ampullae of Lorenzini) enabling them to detect weak electrical potentials generated by other animals and inanimate objects; these are used principally for locating prey (Kalmijn, 1971). These receptors are highly sensitive at short distances ($\leq 0.5$ m), and a corollary of this high sensitivity is that it is easily saturated by intense stimulation such as that created by an artificial electrical field (Hart and Collin, 2015).

The use of electrical barriers to deter sharks were first assessed (and rejected) by the New South Wales Shark Menace Committee in 1929 (Anon, 1935), and early attempts in South

Africa appeared to fail (Cliff and Dudley, 1992). This approach requires deployment of a series of electrodes spaced within an area and connected to a power source that generates an electric current. Personal electrical deterrents based on similar approaches have been found to deter sharks (albeit not 100% of the time) (Smit and Peddemors, 2003; Huveneers et al., 2018a and b). Currently there are no scientifically proven and commercially available electrical deterrents for large-scale area use. Research on developing practical and effective approaches is ongoing, but the results are yet to be published in the scientific literature. A challenge with undertaking field evaluations of such deterrents is the need for testing locations to be located in water clear enough to record sharks and their behaviour independently and with enough shark encounters to enable statistically robust conclusions. Alternatively, trials could be conducted in areas where long-term telemetry data on shark movements exist and where subsequent activity responses to electrical barriers can be analysed. While all elasmobranchs have ampullae of Lorenzini, their morphology can differ between species (Kajiura, 2001) which leads to the possibility of interspecific differences in responses to area-based electrical deterrents. Field tests should be on at least one of the three most dangerous species to humans, and preferably all three. A person who is pregnant, has a pacemaker, or any other condition that could be affected by an electric field are informed by manufacturers to avoid wearing an electric shark deterrent. The potential impacts of electrical deterrents on animals other than sharks are also a consideration; however, Broad et al. (2010) did not detect impacts on the diversity and abundance of teleost (bony) fish from the use of personal electrical shark deterrents. This was not surprising given bony fish lack ampullae of Lorenzini or analogous organs. However, any large-scale deployment would still need to consider impacts on other fauna including harmless elasmobranchs, bony fishes, reptiles and marine mammals.

Deterrents have also been designed using a combination of permanent magnets and a visual component. The Sharksafe Barrier™ combines barium-ferrite permanent magnets and a PVC piping arrangement to mimic kelp as the piping moves with the waves and currents. Permanent magnets are thought to act on the electro-sensory system of sharks indirectly through electromagnetic induction which is thought to be the same physical mechanism that allows sharks to detect the Earth's magnetic field (O'Connell et al., 2014a). The visual component of the approach was based on observations that white sharks appear not to readily enter kelp forests (O'Connell et al., 2014b). The rationale of using both the visual and magnetic components in the barrier is to maximise the performance of the physical barrier across circumstances where turbidity may vary by providing different stimuli detectable by two of the shark's sensory systems. However, from the trials undertaken to date the importance of the magnetic component of the barrier is still uncertain (O'Connell et al., 2014a, 2018). Trials of the Sharksafe Barrier™ have been effective at modifying the behaviour of both white and bull sharks with both being effectively excluded from an area of deployment (O'Connell et al., 2014a and b, 2018). Although the system was durable in a high energy coastline, the spatial scale (tens of metres) of experiments were small relative to the area that is needed to be effective for ocean users. The potential for habituation by sharks to the stimuli remains to be assessed, especially considering the recent discovery that white sharks enter dense kelp forests to hunt seals (Jewell et al., 2019).

Since the 1930s, bubble curtains have been proposed as a method for deterring sharks from entering an area by creating a visual barrier (Anon, 1935). A bubble curtain generates air (e.g. through a compressor) along a submerged, perforated hose which escapes from the perforations and rises to the surface, resembling a curtain. This this approach showed early promise in tank trials, however, subsequent trials identified only very limited deterrent abilities as the animals habituated to the bubble curtains (Gilbert, 1968). While there is renewed interest in bubble curtains as a shark deterrent (Hart and Collin, 2015), no new independent assessments have provided evidence to support their effectiveness.

Acoustic deterrents have been proposed to mitigate shark bite and sharks are known to be sensitive to low-frequency sounds up to 2000 Hz and have a peak sensitivity at around 100 Hz (Hueter et al., 2004). There has been focus on recording and replaying orca (*Orcinus orca*) calls as a deterrent since orcas include elasmobranchs in their diet (Reyes and García-Borboroglu, 2004, Engelbrecht et al., 2019). Chapuis et al. (2019) assessed the behavioral response of seven shark species to orca calls and novel sounds and identified that responses varied between species and individuals. The acoustic stimuli alone were not an effective deterrent for white sharks, even though orca appear to displace white sharks following predation events (Pyle et al., 1999, Jorgensen et al., 2019). Ryan et al., (2018) also found that acoustic deterrents using novel sounds did not significantly reduce feeding in three shark species including the white shark. We found no studies on the efficacy of acoustic deterrents on bull or tiger sharks. The broader environmental impacts of acoustic deterrents on other animals such as cetaceans needs to be considered but has not been the focus of specific research to date.

The development of chemical deterrents can be dated to at least 1942 with the U.S military conducting research in response to the fear servicemen had of sharks (Baldridge Jr., 1990; Stroud et al., 2014; Hart and Collin, 2015). In addition to actually deterring a shark, chemical deterrents need to be non-lethal to sharks and other marine animals, be able to be synthesized and stored without denaturing for a sufficient period of time, and be effective in relatively small volumes to allow for practical use (Baldridge Jr., 1990; Hart and Collin, 2015). When these factors are considered chemicals, which elicit avoidance responses in sharks are unsuitable as a deterrent or repellent. Pardaxin and pavonin are toxins derived from soles (Soleidae: *Pardachirus* spp.) which can repel sharks but are unsuitable as they lose potency when freeze-dried for long periods of time (Hart and Collin, 2015). Chemicals such as sodium dodecyl sulphate (SDS) generally require a volume of chemical that is too large for practical use in the field and may have broader environmental impacts (Baldridge, 1990). Surfactants such as sodium lauryl sulphate which is used in many common household goods (e.g. shampoos and laundry detergent) can elicit a response if delivered directly to the mouth of a shark (e.g. via a squirt gun), but is ineffective as a repellent when released at low concentrations (Smith Jr., ,1991; Sisneros and Nelson, 2001). A more recent focus on chemical deterrents has been for personal use rather than for broader deployment and based on biological compounds (semiochemicals) rather than those that are an irritant to shark senses (Hart and Collin, 2015). Some of these are based on necromones in decomposing shark tissue which contain high concentrations of acetic acid and a large array of amino acids, short chain and fatty carboxylic acids, amines and short chain lipid oxidation products (Stroud et al., 2014). The RepelSharks™ personal chemical deterrent proved to disperse competitively feeding Caribbean reef sharks (*Carcharhinus perezi* and *C. acronotus*) (Stroud et al., 2014). However, trials on the key dangerous sharks have not been published, and it is plausible that necromones may stimulate feeding in shark species that scavenge on other sharks, including white and tiger sharks. Further, applying RepelSharks™ which is deployed currently via a small canister is not feasible at a large scale.

The use of permanent or semi-permanent physical barriers to provide an area from which sharks are excluded is a longstanding approach and represented an early attempt to protect bathers off Durban, South Africa, and Coogee Beach in Sydney, New South Wales (Anon, 1935). However, the impacts of constant wave action, scouring of beach profiles, and biofouling though marine growth on the structures led to failure of both attempts. However, permanent barriers have been effective in marine environments protected from exposed ocean conditions (e.g. Sydney Harbour, New South Wales). The wave energy on many ocean beaches requires that permanent physical barriers be designed to withstand surf conditions at locations of deployment. Engineering designs should assess not only average conditions, but extreme conditions, including scenarios where optimal engineering performance is subject to mechanical drag from biofouling, macroalgae dislodged by wave action or build-up of sediment transported by turbulence or strong currents. Potential for biofouling will be geographically and seasonally variable, and transferability of information on biofouling between locations requires caution. Where permanent physical barriers have been installed in ocean beach environments with success, it has generally been in locations where offshore islands or the coastline topography and bathymetry provide protection from wave action (e.g. Coogee Beach, Western Australia). While physical barriers principally aim to protect bathers, they may also, depending on location, provide protection for surfers. Surfers, however, may actively oppose a permanent physical barrier if it could affect the surfing amenity (Simmons and Mehmet, 2018). Potential for interactions with commercial or subsistence fisheries (e.g. beach hauling) may also be an important consideration in using permanent physical barriers (Davison and Kock, 2014). Potential interruptions to fish migration, sand movement and entanglement of fauna such as marine turtles are also environmental considerations at the local level.

Even when physical barriers are considered as permanent, they may need to be retrieved periodically for maintenance and protection prior to severe weather events. The latter can prevent physical damage to the barriers but may depend on safe and efficient retrieval, often at short notice. Even if this can be done, some structures (e.g. moorings) may not be readily retrievable and thus remain at risk. Finally, where physical barriers do become dislodged from their intended position, they can pose an environmental risk to aquatic habitats, biota or even humans (e.g. by entanglement, navigation hazard , etc.).

Alternatively, physical barriers may be temporary (Davison and Kock, 2014), thus eliminating the need for structures engineered to avoid extreme conditions and biofouling, but may be labour-intensive to deploy and retrieve. Further, the need for structures that are easy to deploy and retrieve also predisposes such structures to being relatively "lightweight" and limited to more protected parts of a coastline. One such temporary physical barrier is deployed and retrieved in a protected corner of Fish Hoek Bay (South Africa), where trained personnel deploy and retrieve the barrier (Davison and Kock, 2014).

## 4. Guidelines for establishing protection from potential shark bite

A beach authority considering non-lethal methods to mitigate the risk of shark bite should identify which systems had been proven to work against the shark species of concern. Further considerations include costs of establishment and maintenance, user groups each system could adequately protect (i.e. bathers or surfers), the potential for impacts to other water users and optimal operating conditions for each system. While costs are important, it was beyond the scope of this paper to quantitively compare the costs of various methods. Costs will be dependent on several factors including labour costs, existing infrastructure and local environmental conditions. A key outcome from this review has been that, with few exceptions there was a general paucity of peer-reviewed information about the likely effectiveness of most of the non-lethal approaches, either generally or in specific circumstances.

The major types of mitigation of shark bite, and logistical, environmental, and financial considerations are identified in **Table 1**. We also identify methods that have been subjected to peer review. The matrix presented is intended to assist policy makers and managers in deciding upon the most suitable method(s) for the conditions in their areas of concern.

Many methods are applicable to several situations/conditions identified. In such cases costs will be a key consideration, both capital and operating. Costs may be scalable meaning many of the systems would be ruled out on cost alone if the objective were to protect many beaches rather than a few selected beaches. For example, in considering detection systems, the high costs of an aerial shark detection system would potentially be problematic if fixed wing or helicopter platforms were to be used for a small number of beaches, and the lesser cost of drones may be acceptable, particularly if operated by lifeguards who are already working to protect water users at patrolled beaches. On the other hand, if many beaches required consideration, the economies of scale of fixed wing or helicopter platforms for large areas can be an advantage and hence these detection systems are presently the most commonly used alternatives to lethal approaches over long stretches of coastline. In other circumstances, shark spotting towers could be considered the most cost-effective choice for a small municipality, given it is likely that there would be funds available to build them and especially if the seabed is shallow (< 3 m depth) allowing for easy and rapid detection of an approaching shark. However, authorities need to consider calculating the angle of refraction in determining height above sea level for observers or cameras.

For many systems, the servicing costs need to be considered as all systems, especially equipment moored in the sea, require regular maintenance. The servicing costs for a SMART drumline system, for example, are high given a contractor is required to be 'on-call' to unhook and translocate animals (**Table 1**). However, even systems such as fixed barriers would still need to be regularly cleaned of fouling organisms and checked for breaches.

Based on current knowledge, none of the systems will be able to ever deter or detect 100% of sharks and, given the great difficulties associated with field-testing effectiveness of most of the systems against the shark species of concern, the precise levels of effectiveness for systems may never be truly known. Even barriers, which would be the closest to 100% deterrence, can occasionally tear, potentially allowing a dangerous shark to enter inside the barrier[1]. By

[1] The shark bite at Reunion on 30/8/16 occurred inside a damaged barrier: http://www.requinsreunion.fr/index.php/english/35-last-shark-attack-in-reunion-island-a-hole-in-the-net-why-we-thought-it-will-be-ok

deploying any system for mitigating the potential risk of shark bite, a beach authority takes on some level of risk and must weigh this up against the advantages as determined by the best available information about the system and its applicability to a locality. To maximize effectiveness, a beach authority should choose a system that considers the type of water users at risk and local environmental conditions.

Based on their optimal operating conditions, scalability, servicing, and power requirements we provide three examples that may be useful guidance to beach authorities regarding selection of an appropriate mitigation strategy for potential shark bite. Augmenting all approaches is the need to provide education material which includes current information on sharks, and safety tips are a crucial part of any shark safety strategy (Curtis et al., 2012). Safety tips can include information for avoiding conditions where risk of a shark bite may be elevated Examples may include avoiding swimming or surfing in low light levels ,avoiding beaches near estuaries following heavy rain and flooding and avoiding places stranded marine mammals are present.

### 4.2 Small areas of a beach or a few small metropolitan, supervised beaches

If the water clarity is generally good for most of the year and the seas are rarely rough, then nearly all of the systems could be deployed effectively. Here, the systems that offer full day coverage would be more favourable (**Table 1**), particularly those offering real-time information to bathers. If the water clarity was generally poor, then systems relying on visual detection will be inefficient unless multi-spectral cameras are included in aerial surveillance craft. Similarly, underwater cameras would be ineffective in low underwater visibility scenarios; however, other *in situ* detection methods would still be functional. On the other hand, even occasionally rough seas would impact efficacy for almost all currently available detection and deterrent technologies, with the exception of SMART drumlines which can be deployed in moderate sea conditions, although response time to a shark capture may be inhibited. For regions with rough sea conditions the durability of many of the deterrents to the most extreme of the potential conditions would need to be proven, preferably by on-site testing.

If surfers are the focus for protection, then consideration must be given to the appropriate distance offshore for positioning these systems because surfers inevitably are further from the shore than bathers, particularly if the surf is large. As the distance from the shore increases, so does the water depth, thus the systems would need to cover a larger height of water column than where closer to shore. This factor generally limits the effectiveness for protecting surfers of many of the emerging in-water technologies, regardless of beach size.

### 4.3. Many small metropolitan, supervised beaches or large beaches

Where many small beaches or a few large beaches are included in a shark bite mitigation program, the costs associated with scalability becomes an issue for many systems. Thus, the only cost-effective options are shark detection methods. Visual detection using aircraft (manned or unmanned) may provide suitable surveillance for sharks, particularly in shallow, clear waters, which would enable detection of approaching sharks, with shark swimming-speeds possibly contributing to calculation of flight intervals. Further, spotting from headlands may be appropriate under these circumstances only if the costs of labour are small and when the system can be implemented with another system that could cover parts of the beach that spotters cannot effectively survey from the headlands.  In areas where water clarity is low, or sea conditions are rough, visual detection methods will not be sufficiently effective. SMART drumlines can be used in such instances, and physical barriers in more protected waters and/or across small coves are an option.

### 4.4. Remote, unsupervised beaches

The only practical options for an ‘area-based’ shark bite mitigation at remote beaches is manned aerial surveys or real time receivers to detect tagged sharks, although the latter option has high maintenance costs associated with ongoing shark tagging programs and scale-up to many beaches. Both systems need to have the capability of real time reporting of information to bathers and surfers by a method other than via lifeguards, as would be the case on supervised beaches. A waterproof wearable smart-device would be the best conduit although a loudspeaker is used effectively by helicopter crew to communicate the presence of a potentially dangerous shark to surfers in New South Wales. For aerial surveys, the fly-over frequency becomes important and needs to be a sufficient proportion of the day to reduce risk meaningfully. The same issues associated with water clarity and rough seas are also relevant for this case.

## 5. Conclusion

Overall, there is no single universal approach that beach authorities can use to mitigate unprovoked shark bite. While no approach will ever be 100% effective a reduction in the risk of shark bite is achievable with well-considered approaches. Beach authorities need to consider site specific environmental factors as well as patterns of human use. This paper has provided guidance on the factors that beach authorities need to consider if required to design non-lethal shark bite mitigation strategies. Research on the effectiveness of approaches will be ongoing and research needs to focus on rigorous experimental testing of approaches under relevant conditions. The cost of various approaches is an important consideration, and this paper has identified that relative costs need to be determined locally considering the cost of labour costs, existing infrastructure and local environmental conditions.

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**Table 1**. Operating situations, potential impacts, environmental conditions, testing status, commercial readiness and costs of shark bite mitigation systems. Y = system meets the criteria. I = insufficient information available. H = high. M = moderate. L = low.

| | | | | Operating times | | Location | Sea state | | | Water clarity | | | Beach attribute | | | Other potential impacts | | | Peer-reviewed scientific testing of method and whether tested on white, bull or tiger shark | | | | Commercial readiness / comparative expense | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Part day | Full day | Can operate at remote beaches[1] | Slight | Mod | Rough | Poor | Mod | Good | Sheltered | Exposed | Headland | Non-dangerous species | Human health | Other water users | White | Bull | Tiger | Methods | Commercially available | Capital costs | Operating costs |
| DETECTION | Aerial | Manned | Fixed wing | Y | | Y | Y | Y[2] | | | Y[2] | Y | Y | Y | Y | | | | Y | Y | | Y | Y | H | H |
| | | | Helicopter | Y | | Y | Y | Y[2] | | | Y[2] | Y | Y | Y | Y | | | | Y | Y | Y | Y | Y | H | H |
| | | Unmanned | UAV | Y | | | Y | Y[2] | | | Y[2] | Y | Y | Y | Y | | | | | | | Y | Y | L | L |
| | | | Balloon | Y | | | Y | Y[2] | | | Y[2] | Y | Y | Y | Y | | | | | | | | | M | L |
| | Land-based | Manned | Beach level | Y | | | Y | | | | Y | Y | Y | Y | Y | | | | | | | | Y | L | L |
| | | | Towers (>40m) | Y | | | Y | | | | Y | Y | Y | Y | Y | | | | | | | | | L | L |
| | | | Headland (Shark spotters) | Y | | | Y | | | | Y | Y | Y | Y | Y | | | | | | | Y | Y | L | M |
| | In-water | Remote | Sonar | | Y | | Y | Y | | Y | Y | Y | Y | Y | Y | I | | I | | | | Y | Y | H | H |
| | | | Cameras | _ | Y | | Y | Y | I | | Y | Y | Y | Y | Y | | | | Y | | | Y | Y | M | H |
| | | | Divers | _ | Y | | Y | | _ | | Y | Y | Y | Y | Y | | | | | | | | Y | M | H |
| | | | VR4G | | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | | | | Y | Y | Y | Y | Y | H | H |
| | | Capture | Smart drumline | | Y | Y[4] | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | | I | Y | Y | Y | Y | Y | M | H |
| DETERRENT | Sensory | Visual | Lights | | Y | | Y | Y | Y | Y | Y | Y | Y | Y | Y | I | | I | | | | Y | | M | L |
| | | | Bubble curtain | | Y | | Y | Y | | Y | Y | Y | Y | Y | Y | | | | | | Y | Y | | M | M |
| | | Visual & Magnetic | SharkSafe Barrier | | Y | | Y | Y | I | Y | Y | Y | Y | Y | Y | | | I | Y | Y | | Y | | M | L |
| | | | Aversive sound | | Y | | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | | I | | | | Y | Y | M | L |
| | | Electric | Electric barrier | | Y | | Y | Y | I | Y | Y | Y | Y | Y | Y | Y | I | I | Y[3] | Y[3] | | Y[3] | Y | M | M |
| | | Olfaction | Chemicals | | Y | | Y | Y | Y | Y | Y | Y | Y | Y | Y | I | | | | | | Y | Y[3] | M | M |
| | Barrier | Non-capture fence/net | Permanent | | Y | | Y | | | Y | Y | Y | Y | I | | Y | | Y | | Y | | Y | Y | M | L |
| | | | Temporary | Y | | | Y | | | Y | Y | Y | Y | Y | | Y | | Y | | | | Y | Y | L | M |

[1] Unsupervised beach with no lifeguards, [2] Only with multispectral camera, [3] Personal deterrent only, [4] Only if port nearby