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## 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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1    **Abstract**

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

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

14

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17

## 18     **1. Introduction**

19

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

31     Responses to unprovoked shark bite involve public policies and management approaches that  
32     contend with the needs of public safety and the responsibility to protect threatened species  
33     (McPhee, 2014; Pepin-Neff and Wynter, 2018). Management agencies may implement  
34     measures that attempt to reduce bite risk, address public concern, or provide warning systems  
35     to identify the presence of sharks at a beach in real-time. In two Australian states (Queensland  
36     and New South Wales) and South Africa, methods that use fishing apparatus to capture and kill  
37     large sharks adjacent to popular beaches are a long-standing approach aimed at reducing the  
38     probability of an unprovoked shark bite (Cliff and Dudley, 1992; Sumpton et al., 2011). Two  
39     types of fishing apparatus are used – mesh nets or drumlines (**Figure 1**). These two measures  
40     have become highly controversial (Meeuwig and Ferreira, 2014; Gibbs and Warren, 2015;  
41     Simmons and Mehmet, 2018; Gibbs et al., 2020) due to a realisation of the low risk to humans  
42     posed by most sharks, the conservation status of some shark species, the role of many sharks

43 as apex predators, the recognition of the need to reduce the overall anthropogenic mortality on  
44 shark species from various sources, and changes in public perception towards the intrinsic  
45 value and ecosystem benefits of sharks (Simpfendorfer et al., 2011; O'Connell and deJonge,  
46 2014; Gibbs and Warren, 2015; Pepin-Neff and Wynter, 2018). It is also due to the bycatch  
47 captured using these methods (including marine turtles and marine mammals), despite the  
48 efforts to reduce it through gear modifications and timing of deployment (Dudley and Cliff,  
49 2010; Sumpton et al., 2011). There is a recognised need to use non-lethal methods including  
50 new technologies that provide for enhanced safety and peace-of-mind for beach users, while  
51 reducing or eliminating significant environmental impact (Meeuwig and Ferreira, 2014; Gray  
52 and Gray, 2017; Simmons and Mehmet, 2018). This need is principally focused at ocean  
53 beaches where there are many water users (particularly bathers and surfers), although the issue  
54 can extend to other marine habitats (e.g. reefs, estuaries and rivers).

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

67

68     **2. Occurrence of Potentially Dangerous Sharks and Consideration of Local**  
69     **Conditions.**

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

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

88     **3. Overview of the Alternative Approaches.**

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

92 Shark detection can include methods that: a) use aerial views over the beach, through an  
93 aircraft (manned fixed wing or helicopter (e.g. Robbins et al., 2014), or unmanned aerial  
94 vehicles (e.g. Colefax et al., 2019; Butcher et al., 2020) or balloon ( Kiszka and Heithaus,  
95 2018)) or personnel on land to detect and identify a potentially dangerous shark (Oelofse and  
96 Kamp, 2006; Kock et al., 2012), b) are in-situ and aim to detect a previously tagged shark (e.g.  
97 Hazin et al., 2013; Bradford et al., 2011), and c) are in-situ and aim to detect all sharks (tagged  
98 and untagged) within a defined area (e.g. Parsons et al., 2014). To be effective as a direct  
99 protection method, information regarding the presence of a large shark needs to be  
100 communicated to water users in real time (Bradford et al., 2011).

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

109

### 110 **3.1 Detecting Sharks – Aerial Surveys and Land based Approaches.**

111

112 Aerial surveys have been used to assess abundance and distribution of several shark species  
113 (Wilson, 2004; Cliff et al. 2007; Rowat et al., 2009; Dicken and Booth, 2013; Kaijura and  
114 Tellman, 2016). Variables that limit the effectiveness of the aerial surveys include water clarity,  
115 wind strength, sea chop, water depth and the behavior of the shark species themselves (Robbins  
116 et al., 2014; Colefax et al., 2018; Butcher et al., 2019). In the context of beach protection, these

117 limitations can, result in inaccurate assessment of risk to beach users. They are also relevant  
118 variables to consider for land-based approaches (Engelbrecht et al., 2017).

119

120 *Manned aerial surveys:*

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

126 Robbins et al. (2014) specifically assessed the efficacy of manned aerial surveys (helicopter  
127 and fixed wing aircraft) to detect sharks for beach safety by deploying and trying to detect  
128 shark analogues. Even with good water clarity (approx. 6 m), observers in fixed-wing or  
129 helicopters could detect the shark analogues only if they were shallower than 2.5 m and 2.7 m  
130 below the water surface, respectively. During subsequent work with analogues placed less than  
131 2.5 m underwater, observers still recorded sightings very infrequently, with overall sighting  
132 rates of only 12.5% and 17.1% for fixed-wing and helicopter observers, respectively. Although  
133 helicopter observers had consistently higher success rates of sighting analogues within 250 m  
134 of their flight path, neither aircraft observers sighted more than 9% of analogues deployed over  
135 300 m from their flight paths. Overall, the low rates of detections found by Robbins et al. (2014)  
136 led them to express serious doubts on the efficacy of manned aerial beach patrols (using human  
137 observers) as an effective early-warning system to prevent shark bites.

138

139

140

141

142 *Unmanned aerial surveys:*

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

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



166 rather than shark analogues and over a range of conditions including conditions present along  
167 ocean beaches.

168

169 *Land-based shark spotter programs:*

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

184 The program is effective only when spotters are in place (0800 to 1800 in South Africa).  
185 While sea state and weather condition affect the likelihood of sighting a shark, this limitation  
186 can be incorporated into the warning system, as per the black flag used in South Africa to  
187 denote when spotting conditions are poor (Engelbrecht et al., 2017). Additionally, the aspect  
188 of the beach relative to the sun influences glare. At beaches which face east or west, glare from  
189 the sun may reduce the reliability of spotting in the mornings or afternoons, respectively.  
190 Further, the issue of fatigue of observers needs to be managed. These factors affecting the

191 ability of dedicated spotters to sight sharks have not been scientifically tested and require  
192 independent determination of shark presence through, for example, aerial confirmation or  
193 acoustic tracking of tagged sharks through the area.

194

### 195 **3.2 Detecting Sharks – Tagged Animals.**

196

197 Telemetry projects on sharks occur world-wide (e.g. Hammerschlag et al., 2011; Hussey et  
198 al., 2015), but their project design has seldom focused specifically on shark bite mitigation  
199 (McAuley et al., 2016). Potentially dangerous sharks can undertake large scale movements  
200 which cover numerous habitats and nearshore conditions (Bruce et al., 2006; Heithaus et al.,  
201 2007; Heupel et al., 2015). Telemetry studies on bull, tiger and white sharks have yielded  
202 information on their movements and patterns of habitat use in coastal waters which is relevant  
203 to bather safety (Blaison et al., 2015; McAuley et al., 2016; Smoothey et al., 2019; Niella et  
204 al., 2020). However, in order to provide information on tagged shark presence to beach users  
205 any telemetry array would need to be at a fine scale and deployed to ensure tagged sharks have  
206 maximum likelihood of being detected (McAuley et al., 2016). Engelbrecht et al. (2017) and  
207 Kock et al. (2018) demonstrated that such studies over time can provide significant information  
208 which identifies areas and times where overlap between sharks and humans is elevated.

209 Acoustically-tagged sharks can be detected by arrays of fixed receivers that either log the  
210 presence of the tagged shark for future download by the receiver owners or send the record in  
211 near-real time to the owner (Bradford et al., 2011). Alerts for tagged sharks of relevant species  
212 can then be communicated to the public via social media, dedicated websites and text messages  
213 to subscribers. However, managing public fear is potentially complex when using these real-  
214 time listening stations as the sharks may be detected 1km off the beach (assuming a 500m

215 detection radius and the station being deployed 500m off the beach), in which case they pose  
216 no risk to beach users, yet they are alerted to the presence of these offshore sharks.

217 The more tagged sharks of relevant species that are utilising coastal areas the greater the  
218 likelihood of a detection at a beach where a receiver is present. Maintaining receivers in  
219 position requires mooring designs informed by knowledge of longshore sand movement and  
220 regularity of scouring events, plus oceanographic conditions and severe weather events  
221 potentially encountered in the region. Placement of receivers should be such that they provide  
222 the detection swath relevant to the local site. Studies have been conducted to determine  
223 effective range of detection for acoustic tags under varying environmental conditions (Kessel  
224 et al., 2015; Huveneers et al., 2016), a critical factor to consider when designing an acoustic  
225 receiver array for protection against unprovoked shark bite. As well as maintaining these  
226 receivers in place, an ongoing shark tagging program is required as new cohorts of sharks of a  
227 size potentially capable of biting a human will annually recruit into the population and may be  
228 present along coastlines. These factors subsequently can lead to an expensive ongoing shark  
229 tagging program for the management agency responsible for beach safety. In many cases, the  
230 cost is likely to be prohibitive for many management agencies, particularly in developing  
231 countries. Where possible, partnerships between management agencies at different levels of  
232 government and relevant institutions can share the cost burden and provide large-scale  
233 assessment of animal movements such as those achieved through national programs e.g. the  
234 Integrated Marine Observation System Animal Tracking Program in Australia (Harcourt et al.,  
235 2019), or through more localized species-specific collaborations such as the Shark Monitoring  
236 Network in Western Australia which involves Commonwealth and State government agencies,  
237 Australian universities and international support (McAuley et al., 2016).

238

239

### 240 3.3 Detecting Sharks – Untagged Animals.

241

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

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

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

265 A final method of detecting presence of potentially dangerous sharks is via their capture  
266 using fishing gear. The capture and release of sharks can result in physiological stress for the  
267 animals and potential mortality (Skomal et al., 2007; Marshall et al., 2012, 2015). Capture by  
268 fishing gear is clearly not always a non-lethal method, but technological and operational  
269 improvements have resulted in the release of captured sharks with improved survivorship. The  
270 South African and New South Wales shark bite mitigation programs release all live sharks, but  
271 high mortality rates occur (> 80%) for large ‘target’ sharks caught in the nets (Cliff and Dudley,  
272 2011; Dalton et al., 2017). Survivorship on traditional drumlines in Queensland were 25.9%  
273 for bull sharks, 31% for tiger sharks, and 47.4% for white sharks (Sumpton et al., 2011). The  
274 first ‘green strategy’ for mitigation of shark bites was initiated off Recife, Brazil, using  
275 longlines and drumlines to catch sharks for relocation offshore in waters more than 25 m deep.  
276 Survivorship rates for tiger and bull sharks in these hook-based fisheries were 82.4% and 50%,  
277 respectively, but no differentiation is provided for longline versus traditional drumline  
278 mortality rates (Hazin and Afonso, 2014). Gallagher et al. (2014) also found that survivorship  
279 was higher for tiger sharks compared to white sharks.

280 Recently, a new shark fishing device known as the Shark-Management-Alert-in-Real-Time  
281 (SMART) drumline was invented to maximise survival rate of captured animals (Guyomard et  
282 al., 2019). SMART drumlines include a GPS satellite buoy and a ‘Catch-A-Live’™ system  
283 alerting fishers when an animal is caught in near-real time. The alert is initiated when the bait  
284 is taken by an animal and the magnetic trigger is activated. The approach constitutes a  
285 meaningful compromise between the need to target potentially dangerous species near popular  
286 beaches and the requirement to safely release, and possibly tag captured animals (Guyomard  
287 et al., 2019). They also provide an opportunity to translocate and release offshore any captured  
288 shark, as has been initiated in Brazil (Hazin and Afonso, 2014). Guyomard et al. (2019) found  
289 that 86.9% of animals could be retrieved alive, however, the survival rate varied among species

290 ranging from 94 - 96% for bull and tiger sharks to approximately 46% for scalloped  
291 hammerheads (*Sphyrna lewini*). Similar high levels of live shark releases have been reported  
292 over 3 years of SMART drumline trials in NSW, with 404 white sharks (1 dead), 83 tiger sharks  
293 (all alive), 11 bull sharks (all alive) and 212 non-target animals (5 dead) caught (NSW DPI,  
294 2019). In Western Australia, a year-long trial of SMART drumlines resulted in the capture of  
295 148 sharks and rays with 88% being released in good condition and no recorded mortalities of  
296 any shark species (DPIRD, 2020). The Western Australia trial only resulted in the capture of  
297 two white sharks and this low level of capture compared to New South Wales which was  
298 attributed to differing operational environments, different populations of white sharks, and the  
299 fact that several SMART drumline deployments in New South Wales occurred in known white  
300 shark nursery areas (DPIRD, 2020). Reducing animal mortality requires extra labour expense,  
301 due to standby requirements for rapid response to a capture. Subsequent analysis of  
302 environmental factors associated with captures may lead to understanding conditions affecting  
303 shark abundance and distribution in nearshore waters which can further inform mitigation  
304 strategies. Guyomard et al. (2020) investigated whether the use of baits on SMART drumlines  
305 attracted sharks closer to water users but demonstrated that it was not the case.

306

### 307 **3.4 Area-Based Deterrents.**

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

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

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

338 Deterrents have also been designed using a combination of permanent magnets and a visual  
339 component. The Sharksafe Barrier™ combines barium-ferrite permanent magnets and a PVC

340 piping arrangement to mimic kelp as the piping moves with the waves and currents. Permanent  
341 magnets are thought to act on the electro-sensory system of sharks indirectly through  
342 electromagnetic induction which is thought to be the same physical mechanism that allows  
343 sharks to detect the Earth's magnetic field (O'Connell et al., 2014a). The visual component of  
344 the approach was based on observations that white sharks appear not to readily enter kelp  
345 forests (O'Connell et al., 2014b). The rationale of using both the visual and magnetic  
346 components in the barrier is to maximise the performance of the physical barrier across  
347 circumstances where turbidity may vary by providing different stimuli detectable by two of the  
348 shark's sensory systems. However, from the trials undertaken to date the importance of the  
349 magnetic component of the barrier is still uncertain (O'Connell et al., 2014a, 2018). Trials of  
350 the Sharksafe Barrier™ have been effective at modifying the behaviour of both white and bull  
351 sharks with both being effectively excluded from an area of deployment (O'Connell et al.,  
352 2014a and b, 2018). Although the system was durable in a high energy coastline, the spatial  
353 scale (tens of metres) of experiments were small relative to the area that is needed to be  
354 effective for ocean users. The potential for habituation by sharks to the stimuli remains to be  
355 assessed, especially considering the recent discovery that white sharks enter dense kelp forests  
356 to hunt seals (Jewell et al., 2019).

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



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

379 The development of chemical deterrents can be dated to at least 1942 with the U.S military  
380 conducting research in response to the fear servicemen had of sharks (Baldrige Jr., 1990;  
381 Stroud et al., 2014; Hart and Collin, 2015). In addition to actually deterring a shark, chemical  
382 deterrents need to be non-lethal to sharks and other marine animals, be able to be synthesized  
383 and stored without denaturing for a sufficient period of time, and be effective in relatively small  
384 volumes to allow for practical use (Baldrige Jr., 1990; Hart and Collin, 2015). When these  
385 factors are considered chemicals, which elicit avoidance responses in sharks are unsuitable as  
386 a deterrent or repellent. Pardaxin and pavonin are toxins derived from soles (Soleidae:  
387 *Pardachirus* spp.) which can repel sharks but are unsuitable as they lose potency when freeze-  
388 dried for long periods of time (Hart and Collin, 2015). Chemicals such as sodium dodecyl  
389 sulphate (SDS) generally require a volume of chemical that is too large for practical use in the

390 field and may have broader environmental impacts (Baldrige, 1990). Surfactants such as  
391 sodium lauryl sulphate which is used in many common household goods (e.g. shampoos and  
392 laundry detergent) can elicit a response if delivered directly to the mouth of a shark (e.g. via a  
393 squirt gun), but is ineffective as a repellent when released at low concentrations (Smith Jr.,  
394 ,1991; Sisneros and Nelson, 2001). A more recent focus on chemical deterrents has been for  
395 personal use rather than for broader deployment and based on biological compounds  
396 (semiochemicals) rather than those that are an irritant to shark senses (Hart and Collin, 2015).  
397 Some of these are based on necromones in decomposing shark tissue which contain high  
398 concentrations of acetic acid and a large array of amino acids, short chain and fatty carboxylic  
399 acids, amines and short chain lipid oxidation products (Stroud et al., 2014). The RepelSharks™  
400 personal chemical deterrent proved to disperse competitively feeding Caribbean reef sharks  
401 (*Carcharhinus perezi* and *C. acronotus*) (Stroud et al., 2014). However, trials on the key  
402 dangerous sharks have not been published, and it is plausible that necromones may stimulate  
403 feeding in shark species that scavenge on other sharks, including white and tiger sharks.  
404 Further, applying RepelSharks™ which is deployed currently via a small canister is not feasible  
405 at a large scale.

406 The use of permanent or semi-permanent physical barriers to provide an area from which  
407 sharks are excluded is a longstanding approach and represented an early attempt to protect  
408 bathers off Durban, South Africa, and Coogee Beach in Sydney, New South Wales (Anon,  
409 1935). However, the impacts of constant wave action, scouring of beach profiles, and  
410 biofouling though marine growth on the structures led to failure of both attempts. However,  
411 permanent barriers have been effective in marine environments protected from exposed ocean  
412 conditions (e.g. Sydney Harbour, New South Wales). The wave energy on many ocean beaches  
413 requires that permanent physical barriers be designed to withstand surf conditions at locations  
414 of deployment. Engineering designs should assess not only average conditions, but extreme

415 conditions, including scenarios where optimal engineering performance is subject to  
416 mechanical drag from biofouling, macroalgae dislodged by wave action or build-up of  
417 sediment transported by turbulence or strong currents. Potential for biofouling will be  
418 geographically and seasonally variable, and transferability of information on biofouling  
419 between locations requires caution. Where permanent physical barriers have been installed in  
420 ocean beach environments with success, it has generally been in locations where offshore  
421 islands or the coastline topography and bathymetry provide protection from wave action (e.g.  
422 Coogee Beach, Western Australia). While physical barriers principally aim to protect bathers,  
423 they may also, depending on location, provide protection for surfers. Surfers, however, may  
424 actively oppose a permanent physical barrier if it could affect the surfing amenity (Simmons  
425 and Mehmet, 2018). Potential for interactions with commercial or subsistence fisheries (e.g.  
426 beach hauling) may also be an important consideration in using permanent physical barriers  
427 (Davison and Kock, 2014). Potential interruptions to fish migration, sand movement and  
428 entanglement of fauna such as marine turtles are also environmental considerations at the local  
429 level.

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

437 Alternatively, physical barriers may be temporary (Davison and Kock, 2014), thus  
438 eliminating the need for structures engineered to avoid extreme conditions and biofouling, but  
439 may be labour-intensive to deploy and retrieve. Further, the need for structures that are easy to

440 deploy and retrieve also predisposes such structures to being relatively “lightweight” and  
441 limited to more protected parts of a coastline. One such temporary physical barrier is deployed  
442 and retrieved in a protected corner of Fish Hoek Bay (South Africa), where trained personnel  
443 deploy and retrieve the barrier (Davison and Kock, 2014).

444

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

446

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

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

461 Many methods are applicable to several situations/conditions identified. In such cases costs  
462 will be a key consideration, both capital and operating. Costs may be scalable meaning many  
463 of the systems would be ruled out on cost alone if the objective were to protect many beaches  
464 rather than a few selected beaches. For example, in considering detection systems, the high

465 costs of an aerial shark detection system would potentially be problematic if fixed wing or  
466 helicopter platforms were to be used for a small number of beaches, and the lesser cost of  
467 drones may be acceptable, particularly if operated by lifeguards who are already working to  
468 protect water users at patrolled beaches. On the other hand, if many beaches required  
469 consideration, the economies of scale of fixed wing or helicopter platforms for large areas can  
470 be an advantage and hence these detection systems are presently the most commonly used  
471 alternatives to lethal approaches over long stretches of coastline. In other circumstances, shark  
472 spotting towers could be considered the most cost-effective choice for a small municipality,  
473 given it is likely that there would be funds available to build them and especially if the seabed  
474 is shallow (< 3 m depth) allowing for easy and rapid detection of an approaching shark.  
475 However, authorities need to consider calculating the angle of refraction in determining height  
476 above sea level for observers or cameras.

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

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

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<sup>1</sup> 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>

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

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

500

#### 501 **4.2 Small areas of a beach or a few small metropolitan, supervised beaches**

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

512 sea conditions the durability of many of the deterrents to the most extreme of the potential  
513 conditions would need to be proven, preferably by on-site testing.

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

#### 520 **4.3. Many small metropolitan, supervised beaches or large beaches**

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

#### 533 **4.4. Remote, unsupervised beaches**

534 The only practical options for an 'area-based' shark bite mitigation at remote beaches is  
535 manned aerial surveys or real time receivers to detect tagged sharks, although the latter option  
536 has high maintenance costs associated with ongoing shark tagging programs and scale-up to

537 many beaches. Both systems need to have the capability of real time reporting of information  
538 to bathers and surfers by a method other than via lifeguards, as would be the case on supervised  
539 beaches. A waterproof wearable smart-device would be the best conduit although a loudspeaker  
540 is used effectively by helicopter crew to communicate the presence of a potentially dangerous  
541 shark to surfers in New South Wales. For aerial surveys, the fly-over frequency becomes  
542 important and needs to be a sufficient proportion of the day to reduce risk meaningfully. The  
543 same issues associated with water clarity and rough seas are also relevant for this case.

#### 544 **5. Conclusion**

545 Overall, there is no single universal approach that beach authorities can use to mitigate  
546 unprovoked shark bite. While no approach will ever be 100% effective a reduction in the risk  
547 of shark bite is achievable with well-considered approaches. Beach authorities need to consider  
548 site specific environmental factors as well as patterns of human use. This paper has provided  
549 guidance on the factors that beach authorities need to consider if required to design non-lethal  
550 shark bite mitigation strategies. Research on the effectiveness of approaches will be ongoing  
551 and research needs to focus on rigorous experimental testing of approaches under relevant  
552 conditions. The cost of various approaches is an important consideration, and this paper has  
553 identified that relative costs need to be determined locally considering the cost of labour costs,  
554 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 <sup>1</sup>	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 <sup>2</sup>			Y <sup>2</sup>	Y	Y	Y	Y				Y	Y		Y	H	H		
			Helicopter	Y		Y	Y <sup>2</sup>			Y <sup>2</sup>	Y	Y	Y	Y	Y				Y	Y	Y	Y	H	H	
	Aerial	Unmanned	UAV	Y		Y	Y <sup>2</sup>			Y <sup>2</sup>	Y	Y	Y	Y							Y	Y	L	L	
			Balloon	Y		Y	Y <sup>2</sup>			Y <sup>2</sup>	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	Y	M
VR4G				Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y				Y	Y	Y	Y	Y	H	H
	Capture	Smart drumline		Y	Y <sup>4</sup>	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
	Sensory	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	Y			I			Y	Y	M	L
		Electric	Electric barrier	Y		Y	Y	I	Y	Y	Y	Y	Y	Y	Y	I	I	Y <sup>3</sup>	Y <sup>3</sup>		Y <sup>3</sup>	Y	M	M	
		Olfaction	Chemicals	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	I						Y	Y <sup>3</sup>	M	M
	Barrier	Non-capture fence/net	Permanent	Y		Y			Y	Y	Y	Y	I		Y		Y			Y	Y	M	L		
Temporary			Y		Y			Y	Y	Y	Y	Y	Y	Y	Y		Y			Y	Y	L	M		

<sup>1</sup> Unsupervised beach with no lifeguards, <sup>2</sup> Only with multispectral camera, <sup>3</sup> Personal deterrent only, <sup>4</sup> Only if port nearby