Rapid and cost-effective methods for assessing the effectiveness of personal electrical shark deterrent devices

Nathan S. Hart[1] and Laura A. Ryan[1]

[1]Department of Biological Sciences, Macquarie University, North Ryde, Australia

28th July 2019

ACKNOWLEDGEMENTS

This study was funded by a New South Wales Department of Primary Industries Shark Management Strategy (SMS) Grant. The authors would like to acknowledge the assistance and support of Dr. Charlie Huveneers (Flinders University) and Dr. David Slip (Taronga Zoo). LAR was also supported by an ARC Linkage Grant LP160100333.

EXECUTIVE SUMMARY

- We measured the electric fields emitted by five commercially available electronic shark deterrent devices (in different configurations) to establish the shape and extent of the fields and relate this to known repellent thresholds for sharks.
- Overall, the likely protective distance provided by all the devices is short when considering the known voltage gradients required to repel large, potentially dangerous sharks under different conditions. Moreover, there are marked differences in field strength between the available devices and some will be more effective than others.
- For comparison, the predicted maximum effective distances (from the nearest electrode) based on a repellent field of 3 V m^{-1} for the different devices are given in order of decreasing effectiveness:

Device	Effective deterrent distance in metres (@ 3V m^{-1})
Shark Shield Freedom 7	~0.9 – 1.1
Shark Shield Freedom+ Surf	~0.75
Shark Shield Scuba 7	~0.7
Rpela	~0.26 – 0.45
NoShark – dive version	~0.24

- Based on our measurements and modelling, the Shark Shield Freedom 7 is likely to be the most effective of all the currently available electronic shark deterrents. However, recent field testing with white sharks *Carcharodon carcharias* shows that even this device may not deter all sharks all of the time.
- Based on comparisons with other devices, the NoShark device emits a field that is likely too small to protect the majority of the user's body when worn on only one ankle.
- All devices emit pulsed DC electric fields, but the inter-pulse interval is quite variable and, in some cases, this may reduce the effectiveness of the device because a shark may approach a considerable distance while the device is inactive.
- Through comparison of electrical field gradients and known behavioural thresholds, we show that characterising the physical strength/extent of the electrical field emitted by electrical deterrent devices is a rapid and cost-effective way of assessing the likely effectiveness of similar deterrent devices in future. This may reduce the need for costly behavioural testing with sharks in the wild to evaluate devices, with such tests reserved

only for devices shown to be promising based on measurements of the strength of the emitted field.

- The analytical methods used in the present study can be combined with straightforward measurements of the voltage emitted at a short distance from each device and will be practicable for manufacturers and designers to ensure the device is emitting a field of sufficient strength at the required distance.
- We also attempted to make electrophysiological recordings from the afferent (sensory) nerves in the shark electroreceptive system, with a view to assessing the physiological effects of the different electrical and magnetic deterrents. We were unsuccessful in this aim but generated useful insights for future attempts.
- Further research on the physiological responses of the shark electroreceptive and neuromuscular systems to different electric pulse waveforms is required to assess the effect of differences in pulse duration and repetition rate on perceived stimulus strength.

INTRODUCTION

In recent years, the number of reported shark attacks on humans has increased both in Australia and worldwide (Chapman and McPhee 2016). While attacks are still fortunately rare, each incident garners intense media interest and triggers a divisive debate on the most appropriate methods to mitigate attack risk, with the argument generally focussing on the role of shark nets and drum lines as lethal methods of shark population control. In Australia, the State Governments of both Queensland and New South Wales employ large scale beach meshing programs in an attempt to remove large, potentially dangerous sharks from near shore areas. In addition to the catch of sharks, which may impact ecosystems through trophic cascades (Myers, et al. 2007), such measures also generate significant bycatch of non-target species (Krogh and Reid 1996), and non-lethal alternatives to beach meshing programs are desirable.

There have been a number of promising developments in the use of non-lethal technologies, such as helicopter and drone surveillance, 'smart' drumlines that detect the capture of a shark and allow it to be released alive, and improved tagging abilities that allow the movements of large, potentially dangerous sharks to be tracked in real time. However, most of these technologies are resource intensive and concentrated in specific coastal locations, and the majority of water users will still benefit from the use of effective personal shark deterrent/repellent devices.

A range of personal shark deterrents are available commercially and new products are continually added to the market (reviewed in Huveneers, et al. 2018). However, very few of these products have been subjected to rigorous and independent testing to ensure that they are effective in deterring the three main species of shark responsible for fatal and non-fatal shark attacks: the bull shark *Carcharhinus leucas*, the tiger shark *Galeocerdo cuvier* and the white shark *Carcharodon carcharias* (West 2011).

The deterrent devices that have received the most in-depth testing to date are those that use emitted electrical fields to repel sharks. These devices rely on the fact that sharks have a highly sensitive electroreceptive system that is capable of detecting electric field gradients as low as 5 nV cm^{-1} (500 nV m^{-1}) (Kalmijn 1982; Kajiura and Holland 2002). The electric fields emitted by the devices are generally thought to overload the electrosensory system and may also induce involuntary muscle spasms (Marcotte and Lowe 2008), although the actual reason why sharks find the electric field 'unpleasant' are unclear. The electrical pulse technology was originally developed in South Africa, where extensive testing of the effect of electrical fields on sharks had been conducted (reviewed in Hart and Collin 2015), but has changed little since, with the most significant changes being the physical configuration of the electrodes.

Currently, the best-studied electrical deterrent technology is that currently employed by the SharkShield brand devices marketed by Ocean Guardian. Four independent studies have evaluated the effectiveness of this technology in the original SharkPOD (no longer manufactured), and its derivatives: the Freedom 7 and the Freedom+ Surf, which both emit a similar electrical waveform, albeit with slight differences in field strength (see Results). In each case, the devices were found to be partially effective in deterring *C. carcharias* from approaching a chum bait or an unbaited visual target (Smit and Peddemors 2003; Huveneers, et al. 2013; Kempster, et al. 2016; Huveneers, et al. 2018). There are also other electrical devices on the market, including the surfboard mounted Rpela and the ankle-mounted NoShark (a replacement for the ESDS), but these have not been subjected to the same degree of testing. However, as they all work on the same principle, it is likely that comparisons can be made simply by measuring the strength and extent of the electrical field they emit.

In this study, we compared the electrical fields emitted by the electrical shark deterrents currently available on the market. Using existing data from behavioural tests with some of the same devices, we then predict the effective distance at which the different devices will act to deter sharks. Because the propagation of electrical fields is well understood, it is hoped this approach provides a more rapid and cost-effective method to assess the likely effectiveness of an electrical deterrent, compared to traditional behavioural testing methods. Moreover, it is hoped the results will inform further work that may result in the design of improved electrical devices. We also attempted to directly record the effect of electrical and magnetic stimuli on the electroreceptive system of small sharks in the laboratory.

METHODS

1 Measurement of electrical fields emitted by deterrents

1.1 Deterrent devices tested

We measured the electrical fields emitted by five commercially available electronic shark deterrents (Table 1; Figure 1). Except for the NoShark, which was purchased independently, the devices were provided by the suppliers/manufacturers for the specific purpose of our testing. In the case of the Freedom+ Surf and Rpela devices, the manufacturers provided surfboards with the devices pre-installed. All devices were fully charged following the manufacturers instructions prior to testing.

Table 1. Shark deterrents tested in this study and their approximate cost (December 2018)

Device	Manufacturer	Purpose	Cost (AU$)
NoShark (dive version)	Bluvand	SCUBA diving	550
Freedom+ Surf	Shark Shield (Ocean Guardian)	Surfboard mounted	499
Scuba 7	Shark Shield (Ocean Guardian)	SCUBA diving	649
Freedom 7	Shark Shield (Ocean Guardian)	SCUBA diving, freediving	599
Rpela	Rpela (Surfsafe)	Surfboard mounted	495

1.2 Electric field measurements

Measurements of electrical potential (voltage) were made in seawater (36–37 ppt) that was 3m deep over a sand substrate in calm conditions at Rowlands Reserve, Bayview, NSW, Australia (-33.662529, 151.304137) in 2017 and 2018. Devices were attached to a non-conductive plastic frame to stabilise and orient them during measurement. Surfboard-mounted products were fixed to the top of the frame located at the surface of the water. Products intended for SCUBA divers were mounted at a depth of 1.5m. Electric fields will propagate differently if the source is located close to a dielectric boundary; for example, the water-air interface will contain the field emitted by the deterrents and effectively compresses it into a dielectric half-space. This is most relevant for the surfboard mounted devices, but even for the diver devices, the fields measured in our recording configuration will be stronger than if the devices were mounted at greater depth in very deep water far from the substrate and the air-water interface.

Figure 1. Photographs of the electrical deterrent devices measured in this study. Clockwise from top-left: Freedom 7, SCUBA7, Freedom+ Surf, NoShark and Rpela. The size indicator in each image is a 30 cm ruler with black tape indicating a 10 cm distance.

Electric potentials were recorded at different distances up to 1.5m away from the electrodes of each device following the methods of Kajiura and Fitzgerald (2009). The active electrodes were short chlorided silver wires connected via 5m copper wires to a passive attenuator that reduced the measured voltage by a factor of ~19 (DC to >30kHz) to bring them within the dynamic range of the multifunction data acquisition device (X-series USB-6363, National Instruments) used to digitise the signals. The indifferent (ground) electrode was a large diameter multicore copper wire placed 6m away from the deterrent device under measurement. Voltage samples were acquired with 16-bit resolution at a frequency of 1MHz using custom software written (NSH) in Visual Basic using DAQmx libraries (National Instruments). Repeated voltage measurements were made at each distance and were made in one, two or three orthogonal axes with respect to the longitudinal (electrode-electrode) axis of the device.

The unattenuated maximum voltage emitted at the surface of the device electrodes was also recorded using a Tektronix TDS1001B dual channel oscilloscope (40 MHz bandwidth). The oscilloscope was also used to make dual channel recordings of the pulses occurring simultaneously at each electrode, to establish the timing and polarity of the pulses.

1.3 Data analysis

For each device where the magnitude of the voltage pulse was consistent over time, the mean pulse magnitude was calculated from a sequence of pulses recorded over several seconds and across replicate recordings. The magnitude of the pulses emitted from the NoShark device gets progressively smaller over of a sequence of 14–16 pulses that is repeated periodically and so the mean maximum pulse magnitude was calculated instead. The results for the NoShark thus represent absolute maximum field strengths and it should be remembered the field strength at different times throughout the sequence will be less.

Standard electrostatic formulae were used to model the scalar electric potentials of the devices. Each device was assumed to be a static electric dipole immersed in a dielectric half-space. The radius of each pole (i.e. device electrode) was generally small relative to the distance from the device at which the potential was measured. This means that while the electric field very close to the electrode was likely dependent on electrode size and shape, at a practical distance from the electrode, each electrode behaves as a point charge and was modelled as such. Seawater was treated as a dielectric medium with relative permittivity ϵ_1 of 72. Air has a relative permittivity ϵ_2 of ~1.0006. The electric potentials at a given point *P* (z>0) due to each individual electrode on the device were calculated (Equations 1–4) and then summed according to the superposition principle.

$$V = \frac{1}{4\pi\epsilon_0\epsilon_1}\left(\frac{q}{R_1} + \frac{q'}{R_2}\right) \quad \text{Eqn. 1}$$

where:

$$R_1 = \sqrt{x^2 + y^2 + (d - z)^2} \quad \text{Eqn. 2}$$

$$R_2 = \sqrt{x^2 + y^2 + (d + z)^2} \quad \text{Eqn. 3}$$

$$q' = -\left(\frac{\epsilon_2 - \epsilon_1}{\epsilon_2 + \epsilon_1}\right) q \quad \text{Eqn. 4}$$

The method of images was used to compensate for the boundary effect of the air-sea interface (Figure 2). Using a custom macro written in Excel (Microsoft), the electric charge on the conductors (i.e. each electrode of the device) that gave the best least-squares fit of the model to the measured voltage data was calculated using an iterative procedure.

To display the electric field gradients in the horizontal plane of each device, the same electrostatic equations were implemented in Matlab (version 2018a; The Mathworks, Inc.), using the electrode charge values obtained from the modelling. Isostrength electric field gradient contours were plotted to indicate the extent of the emitted fields. The maximum effective deterrent distance for each device was estimated as the distance from each device electrode—along the longitudinal dipole axis and in the horizontal plane—at which the voltage gradient dropped below 3 V m^{-1}. The value of 3 V m^{-1} is that shown in behavioural experiments to be the minimum electric field strength required to reliably prevent ‘unprovoked’ bull sharks (*Carcharhinus leucas*), i.e. those not actively attracted to a bait and making normal migratory journeys, from crossing an electric barrier (Smith 1974).

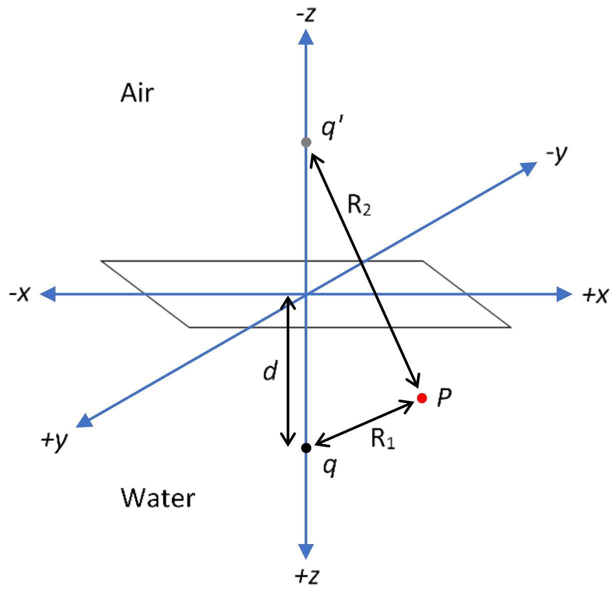

Figure 2. Geometry for modelling the electrical potential generated by a single electrode of a repellent device in a dielectric half space. The horizontal (x, y) plane at z = 0 represents the air-sea interface. q is the charge on the electrode; q' is the mirror charge; d is the distance of the electrode from the surface; P is the location of the voltage measurement.

2 Effects of electrical and magnetic deterrents on the shark electroreceptive system

2.1 Animals

Seven juvenile Port Jackson sharks *Heterodontus portusjacksoni* (mass 180–237 g; TL = 30–34 cm; FL 28–31 cm) that were raised in captivity from eggs were used for the experiments following procedures approved by the Macquarie University Animal Ethics Committee (Animal Research Authority 2017/039). Sharks were housed until use in indoor aquaria under a 12:12h lighting regime.

2.2 Electrophysiological recordings

Sharks were anesthetised using MS222 (ethyl 3-aminobenzoate methanesulfonate salt; Sigma) buffered with an equal mass of sodium bicarbonate (Sigma) and dissolved in seawater. The dose used for induction was 100 mg L^{-1}. After reaching a stage 3 (surgical) plane of anaesthesia, sharks were transferred to the experimental apparatus and anaesthesia was maintained by passing a stream of oxygenated seawater containing 80–90 mg L^{-1} MS222 continuously over its gills via a silicone rubber tube inserted in the mouth (Figure 3A). In some preparations, once a nerve had been dissected free for recording, the seawater containing MS222 was replaced with fresh seawater and anaesthesia was maintained using Alfaxalone (Alfaxan, 10 mg ml^{-1}; Jurox, Australia) at a dose rate of 3 mg every 15 minutes injected intramuscularly.

Following the methods of Dijkgraaf and Kalmijn (1966) the superficial ophthalmic branch of the trigeminal+facial (V+VII) cranial nerves was exposed by dissecting away a small amount of tissue anterior to the forward edge of the crest above each eye (Figure 3B). We attempted to record spiking activity from the nerves using several different electrode configurations, including platinum hook electrodes insulated with a mixture of Vaseline® and mineral oil (Peters and Evers 1985), glass micropipette suction electrodes, tungsten electrodes (12 megaohms resistance), and glass microelectrodes (20 megaohms resistance) (Tricas and New 1997).

2.3 Stimuli

Electrical stimuli were generated using a custom-built apparatus. Voltage signals were created using a USB-6363 multifunction data acquisition device (National Instruments) that was controlled with the manufacturer's device drivers and code libraries (NI-DAQmx 19.1) by custom software written in Visual Basic .NET (Microsoft VB 15.0). Voltages (range 0 to ±10 V) were fed to the non-inverting input of an externally compensated 800 V μs^{-1} slew-rate operational amplifier (LT1361; Analog Devices) wired in unity gain configuration. The output of the amplifier was directly couped to a current-boosting push-pull Darlington transistor output stage that delivered the stimulus to the experimental tank via graphite rod electrodes (6 mm diameter; ~4 cm immersion length). The voltage-drop across the electrodes when immersed in seawater (nominal DC resistance ~15–25 ohms was used to provide negative feedback to the operational amplifier. Low frequency sinusoidal and pulsed DC waveforms (10–1000 $\mu V\ m^{-1}$) were used as probe stimuli to search for electrosensory afferent fibres.

Figure 3. Experimental set-up used to record from electrosensory afferent nerves in anaesthetised juvenile Port Jackson sharks. (A) Shows the anaesthetised shark and the graphite electrical stimulus delivery electrodes; (B) Shows the isolated left superficial ophthalmic branch of the trigeminal+facial (V+VII) cranial nerves that innervates the lateral surface of the rostrum, the lateral line and the ampullae of Lorenzini (electroreceptors); the nerve is shown with two platinum hook electrodes to record compound action potentials from the nerve, prior to the application of insulating grease.

RESULTS

3 Measurements of the electrical fields emitted by the deterrents

Measurements of the physical and electric characteristics of the electronic shark deterrents tested are summarised in Table 2. All devices consisted of an electrical dipole and discharged a pulsed DC electrical field of varying strength. The Rpela field had a fixed polarity in that one electrode/pole was always positive and the other always negative. The other devices alternated the polarity of each electrode, presumably to retard corrosion.

The three devices manufactured by Shark Shield/Ocean Guardian had very similar electrical characteristics, with differences between the devices likely due to changes in the size and shape of each electrode and the spatial separation of the electrodes/poles. The magnitude of the voltage pulse at the surface of the electrode ranged from ±25 to ±46 V, depending on the device. Each pulse lasted ~1 ms and was repeated at the alternate polarity every 650 ms, giving a repetition rate of 1.6 Hz (Figure 4).

The Rpela device had a lower magnitude voltage pulse of ±5 V measured at the surface of the electrode. The duration of each pulse was 0.2 ms and the pulse was repeated every 69 ms, giving a repetition rate of 14.5 Hz (Figure 5).

The magnitude of the pulses emitted by the NoShark device was initially quite large (± 52–65 V at the surface of the electrode) but reduced throughout the sequence of pulses generated periodically by the device. Each sequence consisted of 14–16 pulses of alternating polarity. Each pulse had a mean duration of 0.1 ms and the inter-pulse interval was 150 ms, giving a repetition rate of ~7 Hz (Figure 6). Between each sequence was a gap of 1.8 s when no pulses were generated. The closeness of the two electrodes means that there was likely some self-cancellation by the pulses of opposite polarity emitted simultaneously by each electrode.

For each deterrent device, the extent of the emitted electrical field was estimated (Figures 7 and 8). Based on a threshold deterrent field strength of 3 V m^{-1}, the maximum effective deterrent distance was estimated for each device and was found to range from 0.24 m for the NoShark to 1.09 m for the Freedom 7 (Table 2).

Table 2. Comparison of the physical and electrical characteristics of the electric shark deterrent devices tested in this study

Criterion	Shark Shield Freedom+ Surf	Shark Shield Scuba 7	Shark Shield Freedom 7	Rpela	NoShark
Use	Surfboards	SCUBA divers	SCUBA divers	Surfboards	SCUBA divers
Polarity	Alternating bipolar	Alternating bipolar	Alternating bipolar	Fixed bipolar	Alternating bipolar
Electrode separation	0.9 m	~1.5 m	1.5 m	0.9 m	0.12 m
Electrode 1 (E1)	Flat rhomboid plate	Flat oval plate	Cylindrical mesh	Flat circular disc	Flat mesh
Location	Front	SCUBA tank	Nearest to battery	Front	Nearest to battery
Surface Area	0.009 m^2	0.024 m^2	~0.023 m^2	1.8e-4 m^2	~9e-4 m^2
Maximum voltage (d = 0 m)	±40 V	±46 V	±37 V	>+5 V	+52/-53 V
Electrode 2 (E2)	Flat rhomboid plate	Cylindrical mesh	Cylindrical mesh	Stud	Flat mesh
Location	Rear	Ankle	Furthest from battery	Rear	Furthest from battery
Surface Area	0.009 m^2	~0.019 m^2	~0.020 m^2	2e-5 m^2	~9e-4 m^2
Maximum voltage (d = 0 m)	±40 V	±30 V	±25 V	>-5 V	+65/-60 V
Pulse interval	640 ms (~1.6 Hz)	650 ms (~1.5 Hz)	650 ms (~1.5 Hz)	69 ms (~14.5 Hz)	~150 ms (~7 Hz)
Pulse width	~1 ms	~1 ms	~1ms	~0.2 ms	~0.1 ms
Extended pulse gap	n/a	n/a	n/a	n/a	1.8 seconds gap between a sequence of 14–16 pulses of alternating polarity
Effective distance (d at 3 V m^{-1})	E1/E2: 0.75 m	E1: 0.73 m / E2: 0.66 m	E1: 0.93 m / E2: 1.09 m	E1: 0.45 m / E2: 0.26 m	E1: 0.24 m / E2: 0.24 m
Modelled electrode charge (C)	E1: +8.76E-09 E2: -8.76E-09	E1: +1.2E-08 E2: -1.4E-08	E1: +2.60E-08 E2: -3.3E-08	E1: +9.10E-10 E2: -8.30E-10	E1: +2.47E-9 E2: -2.47E-9

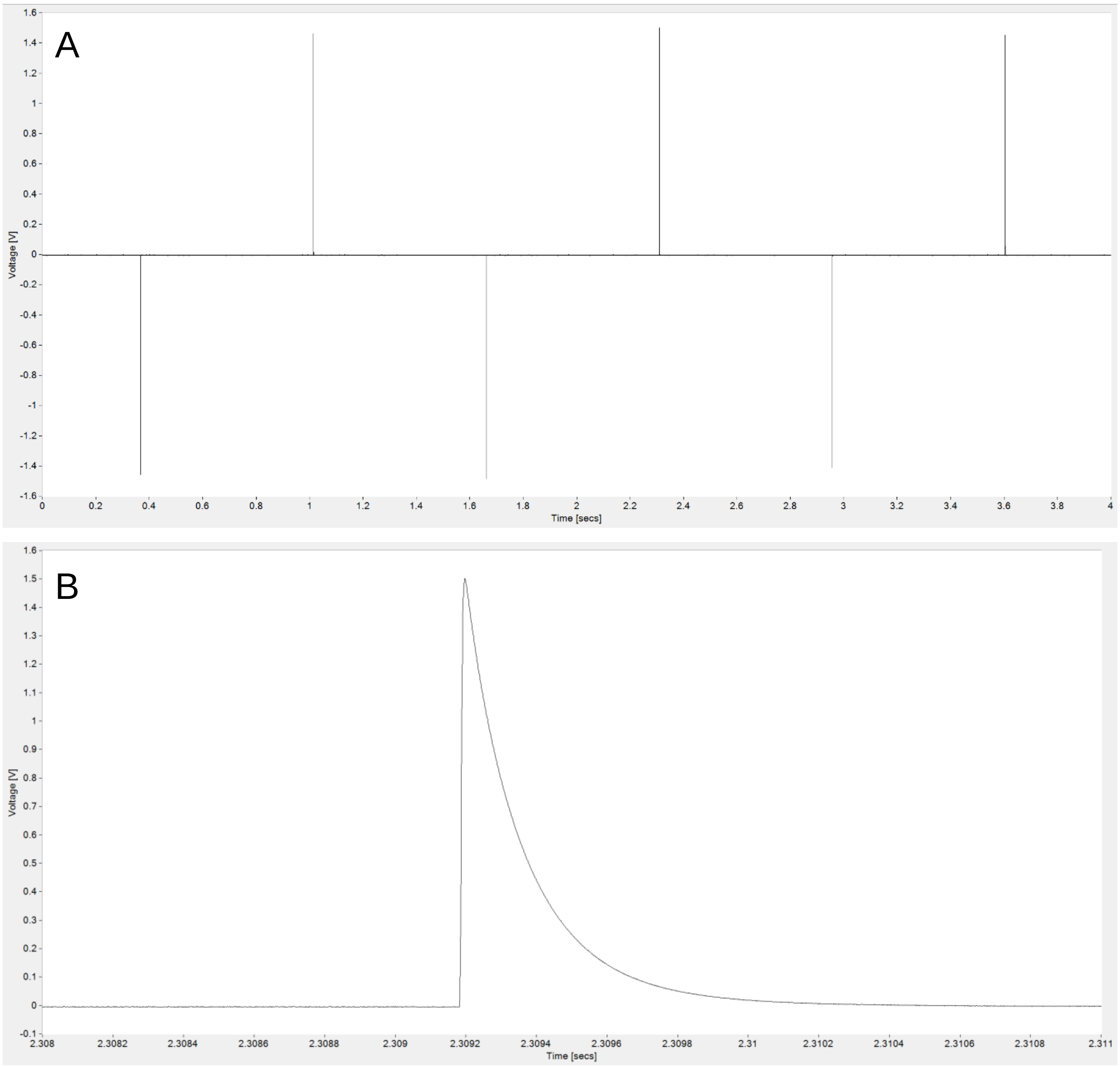

Figure 4. Emitted electrical pulse waveforms for the Shark Shield Freedom 7. (A) Sequence of pulses showing alternating polarity from a single electrode with a pulse frequency of ~1.5 Hz; (B) A single positive-going pulse of ~1 ms duration.

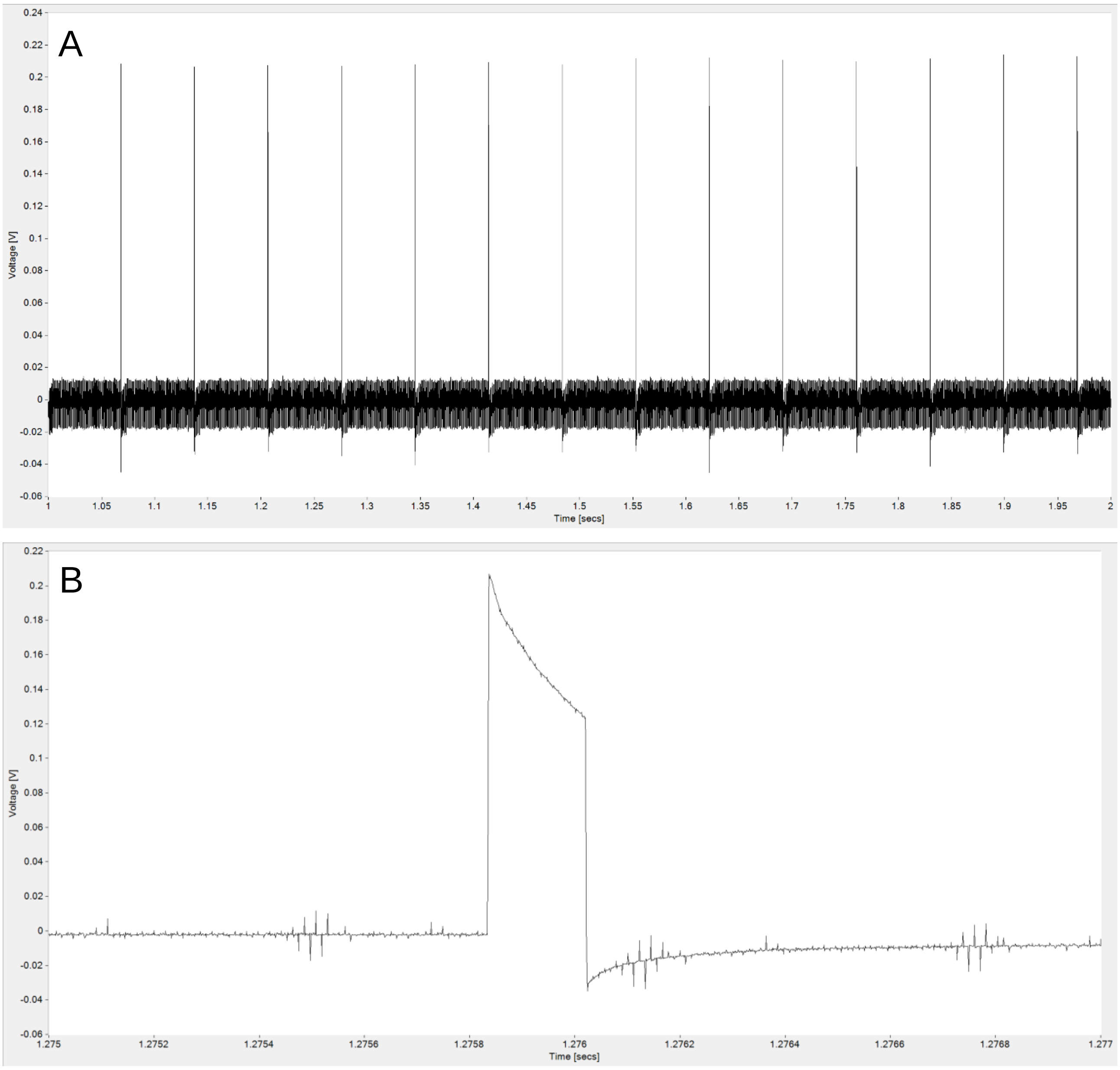

Figure 5. Emitted electrical pulse waveforms for the Rpela. (A) Sequence of pulses showing fixed polarity from a single electrode with a pulse frequency of ~14.5 Hz; (B) A single positive-going pulse of ~0.2 ms duration.

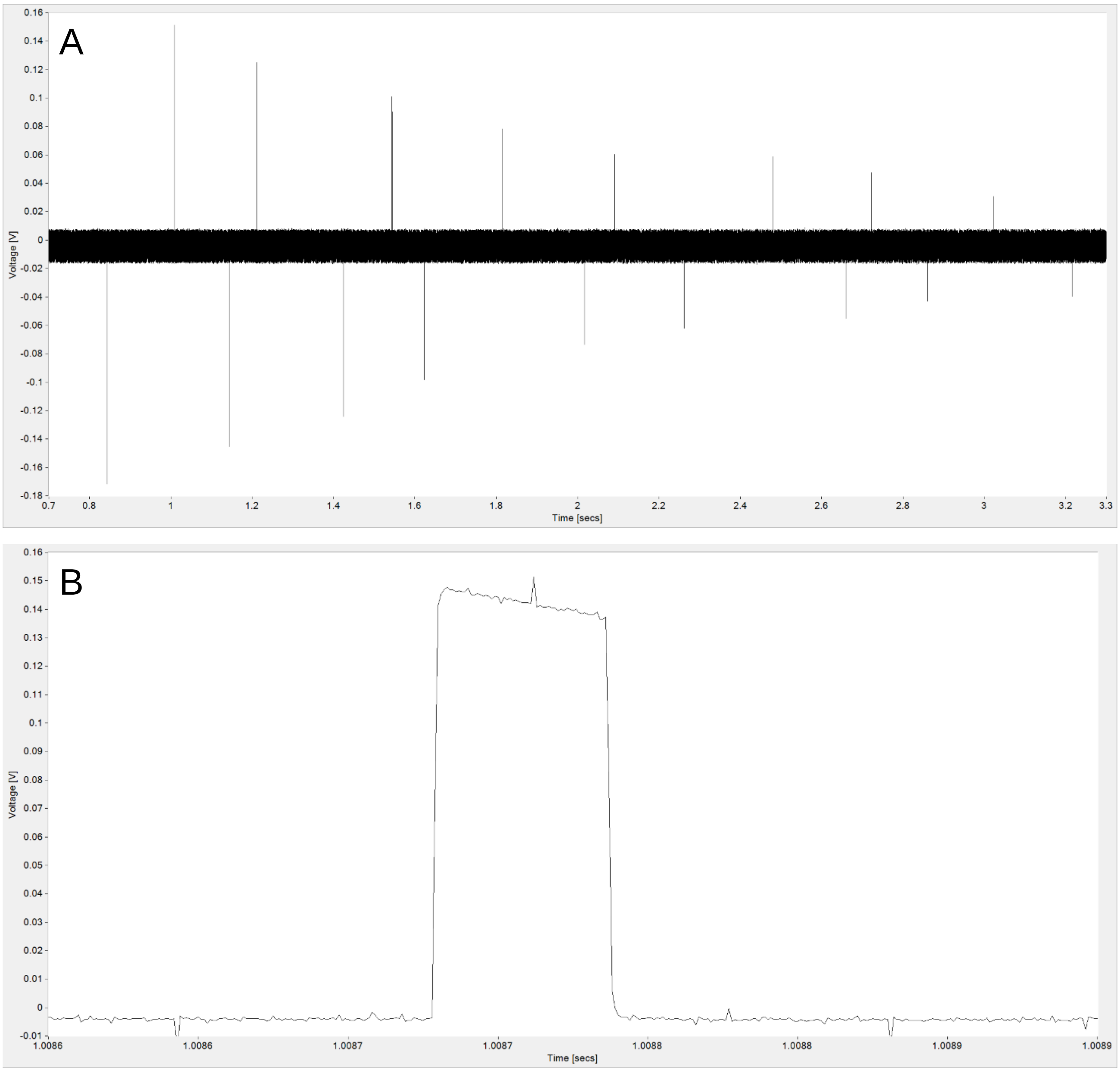

Figure 6. Emitted electrical pulse waveforms for the NoShark. (A) Sequence of pulses showing fixed polarity from a single electrode with a pulse frequency of ~7 Hz; (B) A single positive-going pulse of ~0.1 ms duration.

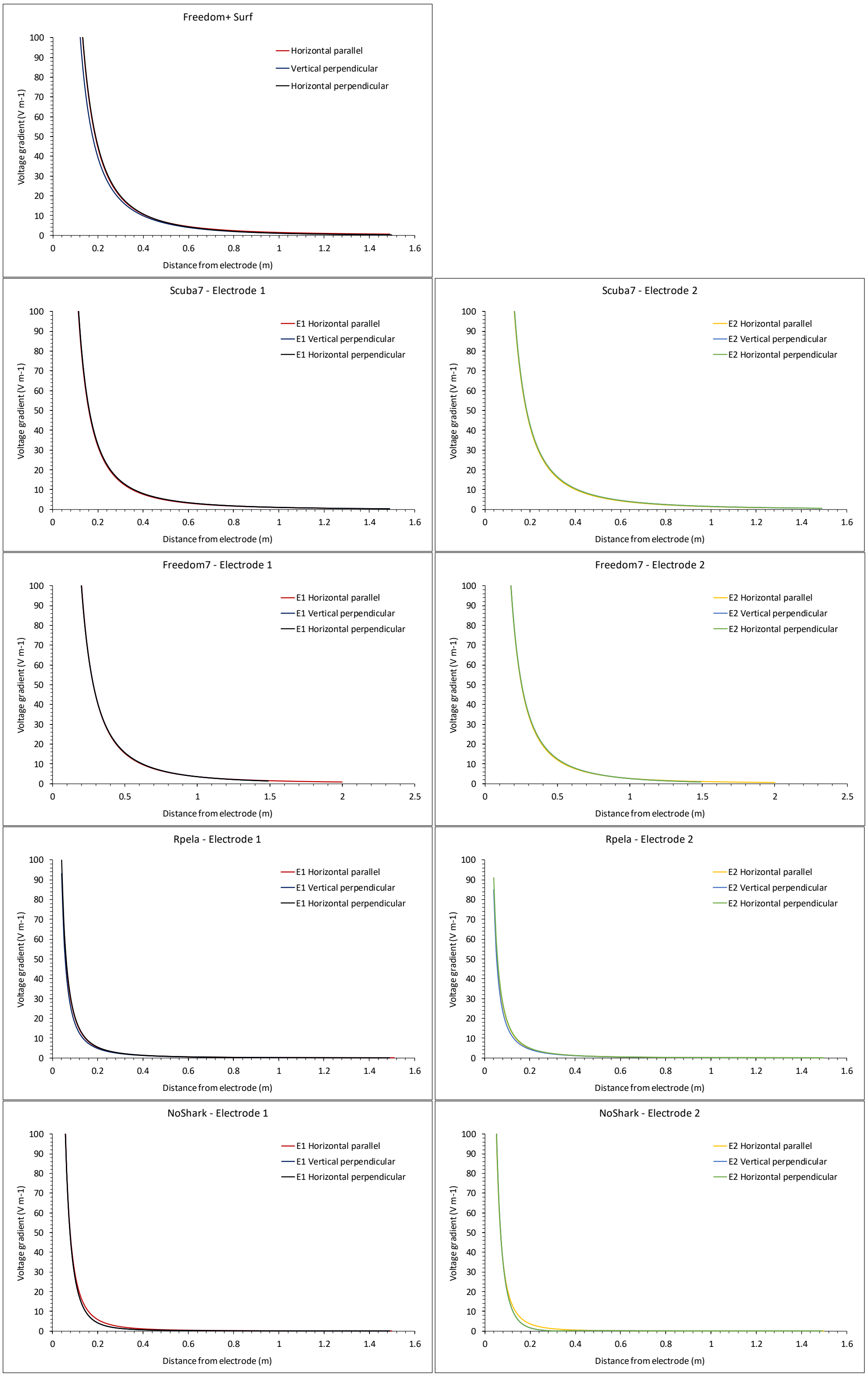

Figure 7. Modelled voltage gradients of the electric fields emitted by the shark deterrents measured in this study. Each curve was obtained by finding the least-squares best fit of the standard electrostatic field equation to electrical potentials measured at different distances from each electrode. Distance zero is equivalent to the centre of one electrode of the device. Both electrodes in the Freedom+ Surf had the same emission characteristics.

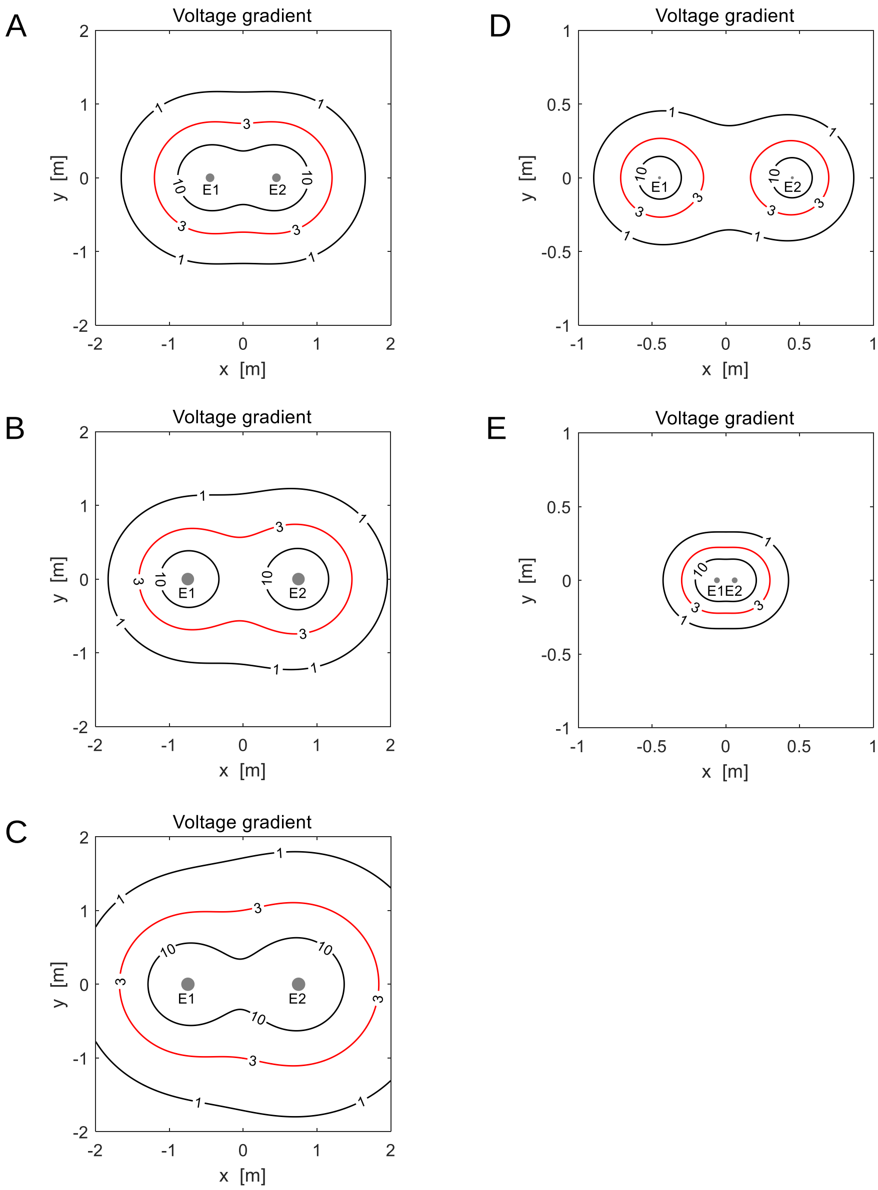

Figure 8. Two-dimensional electric fields in the horizontal plane of the shark deterrents measured in this study, generated using the values for electrode charge estimated by the least-squares best fit method described in the text. The devices are: A) Freedom+ Surf; B) Scuba 7; C) Freedom 7; D) Rpela; and E) NoShark. Electric field gradient isostrength contour lines are shown in V m^{-1}. Devices A and D are located at the surface of the water; the remaining devices are located 1.5m below the surface of the water. Highlighted in red is the 3 V m^{-1} isostrength contour, which represents the electric field strength known to deter potentially dangerous sharks based on previous behavioural studies. Note axis scales differ.

4 Electrophysiological recordings

Despite successfully locating intact electroreceptor sensory afferent nerves in the rostrum, we were unable to record action potentials from individual nerve fibres or compound action potentials from the nerve bundle using any of the electrode configurations. We also attempted to record from the ophthalmic branch of the trigeminal nerve as it passes through the orbit behind the eye but again were unable to detect individual or compound action potentials.

The fish anaesthetic MS222 is known to supress spiking activity in peripheral nerves, but the effect is thought to be reversible (Platt, et al. 1974). Despite flushing the shark's gills and the exposed nerve with fresh seawater and switching to alfaxalone, which is thought to operate on the CNS and affect peripheral sensory nerve function far less (Neiffer and Stamper 2009), we were still unable to record either spontaneous or stimulus-evoked spiking activity. It is possible that even the alfaxalone anaesthesia abolished spiking activity in these peripheral nerves. This meant that we were unable to complete our aim of directly measuring the effect on shark electroreceptors of either electrical or magnetic fields of the magnitude emitted by the personal deterrents.

DISCUSSION

In this study, we mapped for the first time using *in situ* voltage measurements in seawater the extent of the electric field emitted by five commercially available electronic shark deterrents. We found that the electrical fields emitted by these types of electronic shark deterrent can be modelled using relatively simple mathematics describing the scalar electrical potential (voltage) and vector electrical field (voltage gradient) of a static dipole immersed in a dielectric half-space. This has the significant advantage that differences in the size and shape of the electrodes on the device (which differ in surface area by more than one thousand-fold) can be ignored if we are only interested in the strength of the electrical field at a distance that is much greater than the radius of the electrode, which is generally the case. A more accurate representation of the emitted electric fields, especially close to the electrodes, would undoubtedly be gained from integration of a continuous charge distribution model or Finite Element Model, but these methods are computationally intensive and so a simple solution is preferred. The surface area of the electrodes may affect the amount of current that is discharged into the water, as the resistance of an electrode decreases as its surface area increases, reducing the resistance to current flow. This may in turn affect the magnitude of the voltage gradient developed across a given distance of seawater according to Ohms law, although output current will ultimately be limited by the power source and internal electronics of the device.

We found that the extent of the electric field emitted by the devices differed markedly and this implies that they have different effective distances at which they will deter sharks. Based on a threshold deterrent field strength of 3 V m^{-1}, which has been shown through behavioural testing to reliably deter *C. leucas* (Smith 1974), the predicted effective deterrent distance of the device with the strongest field strength, the Freedom 7, was ~1.1 m. In contrast, the device with the weakest field strength, the NoShark, had a predicted effective deterrent distance of just 0.24 m (Table 2; Figure 8). The disappointing result for the NoShark appears to be in part because the electrodes are so close together that the positive and negative polarity pulses emitted simultaneously partly cancel each other out.

A recent study by Huveneers et al. (2018) tested the ability of five different devices marketed as shark repellents to deter white sharks *C. carcharias* from interacting with a bait (tuna head) suspended 0.3 m beneath a surfboard-shaped float. Two electronic shark deterrents were tested, the Rpela and the Freedom+ Surf. Only the active Freedom+ Surf significantly altered the behaviour of the sharks in terms of the number of interactions with the bait, the mean distance between the shark and the bait, and the number of passes made past the bait. In contrast, the active Rpela device did not appear to affect shark behaviour or act as a deterrent under these test conditions.

When active, the Freedom+ Surf reduced the percentage of baits taken from 96% (control) to 40% and increased the mean distance between the shark and the bait from 1.6 m (control) to 2.6 m. The mean distance from the bait at which a 'reaction' by the shark (i.e. a tail flick, muscle spasm, head shake, fast direction change) was observed was 1.7 m (Huveneers et al. 2018). In the configuration tested, the Freedom+ Surf electrodes were separated by ~1.2 m, which means that the shortest distance from the shark to an electrode when it reacted would be ~1.1–1.8 m depending on approach direction. Based on the measurements made in the present study, a distance of 1.1 m from the electrode in the horizontal plane and parallel to the long axis of the dipole corresponds to a field strength of 1.25 V m^{-1}.

An earlier study investigating the effect of the Freedom 7 device on the behaviour of white sharks *C. carcharias* found that the mean proximity of the sharks to a bait attached to the tail electrode (E2 in the present study) of the active device was 1.3 m on first encounter, compared to a mean proximity of 0.4 m for the control condition (Kempster, et al. 2016). Based on the present study, 1.3 m corresponds to a field strength of ~1.35–2.0 V m^{-1}. Taken together with the study by Huveneers et al. (2018), it appears that field strengths of ~1–2 V m^{-1} are capable of inducing avoidance or deterrent responses in *C. carcharias*. However, in each case, sharks still interacted with the bait on a significant number of occasions and so a higher field strength is likely required to deter sharks more reliably.

The NoShark device appears to be a relaunched version of the ESDS (Electronic Shark Deterrent System). The only significant change in electronic design from the ESDS to the NoShark appears to be a reduction in the duration of the extended off period from 2.6 s to 1.8 s, and a reduction in the number of pulses in the sequence from 20 to ~16. Previous work (Egeberg, et al. 2019) using an identical methodology to that used by Kempster et al. (2016) found that the mean proximity (0.27 m) of *C. carcharias* to an active ESDS device adjacent to a chum bait was not significantly different from the control condition (0.27 m). However, the active ESDS device did reduce the proportion of sharks biting the bait (52%) compared to controls (87%). Taken together, this suggests that any repellent effect of the

ESDS extends to <0.27 m. Based on the results of the present study on the NoShark, 0.27 m corresponds to a field strength of ~1 V m^{-1}.

In this study we estimated a maximum effective deterrent distance for each device based on an electric field gradient of 3 V m^{-1}, which is known to repel *C. leucas* and is close to the threshold known to cause avoidance behaviours in *C. carcharias* (see above). It is likely, however, that there is considerable interspecific variation in the strength of the electric field gradient required to elicit a repellent response. Kalmijn (1971) found that cat sharks (*Scyliorhinus canicula*) were repelled by both DC (constant current) and pulsed 5Hz electrical fields of 1 mV m^{-1}, which is very weak compared to that required to repel other shark species. On the other hand, the scalloped hammerhead shark (*Sphyrna lewini*) and the leopard shark (*Triakis semifasciata*) are repelled only by stronger voltage gradients of 18.5 V m^{-1} and 9.7 V m^{-1}, respectively, although behavioural responses (i.e. twitches) were observed at around 4 V m^{-1} (Marcotte and Lowe 2008). Dusky sharks (*Carcharhinus obscurus*) are repelled at ~7–10 V m^{-1} (Smith 1974). Although *C. carcharias* and *C. leucas* are responsible for most of the recorded attacks in Australia and worldwide (West 2011), this variability must be born in mind when the devices are used in circumstances where other potentially dangerous shark species may be present, e.g. tiger sharks (*Galeocerdo cuvier*). Moreover, behavioural tests in *C. carcharias* show that there is considerable intra-specific variation in susceptibility to electric fields and some individuals may be harder to deter than others (Kempster, et al. 2016; Huveneers, et al. 2018). There is also the possibility that some shark species will be attracted to electric fields that are known to deter other species, as found for tiger sharks in the early studies by Gilbert (1970).

When testing electronic shark deterrent devices, bait/chum is typically required to attract enough sharks to provide a statistically robust data set. The presence of food cues in the water may alter the behaviour of sharks or change their sensory thresholds and their susceptibility to painful/unpleasant stimuli. Thus, the electric field strength required to deter sharks in conditions where bait/food cues are absent could be weaker than those reported under baited conditions. However, it must be remembered that under normal circumstances other sensory cues will be present that may attract sharks towards a swimmer or surfer, such as visual, olfactory, vibration or acoustic cues, and so the results of baited testing are not unrealistic.

Another factor to consider is that some devices are found to have a considerably time delay between voltage pulses, especially the NoShark device, which is off for approx. 1.8 seconds between a sequence of pulses. Given that the average cruising speed of medium-large sharks is around 2 m s^{-1} (Ryan, et al. 2015), even a slow-moving shark will travel a considerable distance during this inactive period, certainly more than the predicted effective deterrent distance(<0.25 m). The Rpela device has an advantage in this respect as it has a very short inter-pulse interval and no extended inactive period; however, the Rpela device as configured has a short effective deterrent distance and does not appear to alter shark behaviour under baited test conditions (Huveneers, et al. 2018).

Lastly, the measurements of electric field strength presented here represent instantaneous voltage measurements and do not reflect differences in pulse duration or pulse shape. The importance of pulse characteristics on behaviour may well depend on the system that elicits avoidance behaviour in the sharks, i.e. whether the 'unpleasant' stimulus perceived by the shark is due to overloading of the electroreception system or involuntary muscle spasms or some other mechanism. Knowledge of the stimulus-response characteristics of shark electroreceptors is limited, but based on recordings made in the catshark *Scyliorhinus canicula* (Peters and Evers 1985) and several ray species (e.g. Murray 1962; Tricas and New 1997) their frequency sensitivity is greatest between 1-5 Hz and falls off rapidly above 10 Hz. This means that differences in pulse duration between devices such as the Shark Shield products (~1 ms), the Rpela (0.2 ms) and the NoShark (0.1 ms) (Figures 4–6) are probably of limited importance as the low pass frequency characteristics of the electroreceptors will effectively time-average the pulses. In fact, the relatively high pulse repetition rate of the Rpela (14.5 Hz) might be expected to reduce its effectiveness as the low pass characteristics of the canals and ampullae would serve to smooth out the pulse train.

On the other hand, pulse rate may be of significance if the repellent effect of pulsed electrical fields is driven by involuntary muscle contractions, which may be the case. Based on recordings from isolated electroreceptive ampullae in rays, the maximal firing rate of their afferent nerve is reached at a trans-epithelial voltage of ~100 μV (Lu and Fishman 1994). Given a typical canal length of 10 cm, this would correspond to an external voltage gradient of 10 μV cm^{-1}, which is equivalent to 1 mV m^{-1}. Thus at voltage gradients >1000 times less than those found to cause avoidance behaviour in sharks (e.g. Kempster, et al. 2016; Huveneers, et al. 2018), the electroreceptive system may already be maximally stimulated and incapable of indicating stronger voltage gradients. This leads to the conclusion that—as with the phenomena of electrotaxis and electronarcosis in electrofishing—it is in fact the generation of involuntary muscle spasms (Lamarque 1990) or other neural mechanisms (e.g. electrically induced epilepsy, Sharber and Black 1999) that drives the repellent effect of electrical deterrents. Although there is much published work on the effects of pulsed DC fields on bony fishes, there is a lack of comparable information on sharks and further work in this area may facilitate improvements in the design of electrical repellents.

Unfortunately, in this study, we were unable to make direct measurements of the effect of electronic deterrents on the shark electrosensory system. Previous electrophysiological studies in elasmobranchs have used MS222 for the initial anaesthesia, but once the surgery to expose the neural tissues was completed, the MS222 was replaced with fresh seawater without anaesthetic and instead neuromuscular blockade alone was used to immobilise the animals (Platt, et al. 1974). It is known that MS222 reversibly blocks electrical activity in both peripheral and central neural structures in a dose-dependent fashion, and this may explain our inability to record spiking activity from the afferent electrosensory nerve fibres in the present study. In Australia, the legislation governing the ethical use of animals in research prohibits surgical procedures under neuromuscular blockade without also using anaesthesia or another method of preventing sensory awareness (e.g. brain destruction) and so it was not possible to replicate these prior methods in our experiments. However, even when using alfaxalone, which we have used previously to record the auditory brain stem response in small sharks (Chapuis, et al. unpublished data), we could not record spontaneous or evoked electrical activity. The reasons for this are. Although we were unable to compare the effects of different electrical and magnetic stimuli on the electroreceptive system of sharks, these experiments have the potential to greatly inform our understanding of the mode of action of these deterrent technologies on sharks we will continue to attempt these experiments in future projects.

Overall, this study has predicted differences in the likely deterrent efficacy of the different electronic shark deterrent devices currently available based on the strength of the electric field they emit, and these findings match closely the results of behavioural tests. It has also highlighted some of the challenges in using electric fields to deter sharks. However, some of these electronic deterrent devices are currently the most effective method for deterring potentially dangerous sharks and it is hoped that the results of this study form a basis for future designs and improvements to electrical deterrent technology.

RECOMMENDATIONS

- Based on the measurements made in this study, it is likely that there are considerable differences in the efficacy of the electrical shark deterrents currently available commercially. Given that this has potentially serious consequences for the wearer, caution should be exercised when selecting which device to purchase and/or use.
- The Shark Shield (Ocean Guardian) Freedom 7 device emits the strongest electrical field; the other devices manufactured by Ocean Guardian (Freedom+ Surf and SCUBA 7) have similar albeit slightly weaker fields.
- The Rpela emits a weaker field than the three Shark Shield devices and likely affords less deterrence.
- The NoShark emits a field that is very limited in extent and, based on the results of this study and behavioural tests, may have little or no practical value for the wearer.
- Based on electromagnetic theory and validated by the measurements made in this study, devices functioning as electrical dipoles (i.e. all those studied here) should have electrodes spaced as far apart as possible to prevent self-cancellation by pulses of opposing polarity that are emitted simultaneously.
- All electrical deterrent devices have predicted effective deterrent radii of less than ~1.1 m. This is significant when anticipating the repellent effect of the devices on large, fast moving and motivated sharks. It is no coincidence that in baited tests the devices fail to deter sharks 100% of the time, although some are more effective than others, and wearers should still exercise caution when relying on these devices to protect them from sharks during 'high risk' activities in the ocean.
- For technical reasons, we were unable to make direct measurements of the effect of deterrent-strength electrical (or magnetic) fields on the electrosensory system of sharks. However, based on prior studies in related species and on the measurements made during this study, the electrical fields emitted by all the devices likely exceed the level required to provide maximal stimulation of the electroreceptive system at a distance greater than that shown through behavioural testing to elicit repulsion/avoidance behaviours. This suggests that the deterrent effect of pulsed electrical repellents may not be due solely to overstimulation of the electroreceptive system—as is generally believed— and instead may be due to effects on the neuromuscular system (i.e.

involuntary muscle contractions) or other parts of the central nervous system. Further work on the physiological effects of pulsed electric fields on sharks is required and may facilitate improvements in the design of electronic deterrents.

- Drastic improvements in the strength of the emitted field, which would extend the deterrent radius, are limited by the practicalities of the electronic technology. Because the electric field of a dipole falls off as the cube of the distance from the electrodes, any significant increase in the field strength at a distance would require a significant increase in the emitted voltage (and current). Such increases are constrained by the cost and bulk/weight of the devices and in any case may become so strong close to the user that painful involuntary muscle contractions will make using the devices unpleasant.
- Thus, although some of the electrical deterrents tested are the most reliable and thoroughly tested shark deterrent devices currently available for purchase by the public, further research into alternative technologies—electrical or otherwise—is required.
- Lastly, our research, together with other research funded by the NSW Shark Management Strategy, has already had an impact on the design of commercially available personal shark deterrents. Our electric field measurements and estimates of effective repellent distance were provided on request to the manufacturers of the Rpela surfboard device. Our conclusions on the limited effectiveness of this device were borne out by behavioural experiments with white sharks by Huveneers et al (2018). Rpela has since released an updated (Rpela v2) version of the technology, which is reported to have a stronger emitted electric field. The results of behavioural testing with this new device commissioned by Rpela are available at their website (https://www.rpela.com/rpela-v2-scientific-report-1).

REFERENCES

Chapman BK, McPhee D. 2016. Global shark attack hotspots: Identifying underlying factors behind increased unprovoked shark bite incidence. *Ocean Coast Manage* 133:72-84.

Dijkgraaf S, Kalmijn AJ. 1966. Versuche zur biologischen bedeutung der lorenzinischen ampullen bei den elasmobranchiern. *Zeitschrift für vergleichende Physiologie* 53:187-194.

Egeberg CA, Kempster RM, Hart NS, Ryan LA, Chapuis L, Kerr CC, Schmidt C, Gennari E, Yopak KE, Collin SP. 2019. Not all electric shark deterrents are made equal: Effects of a commercial electric anklet deterrent on white shark behaviour. *PLoS ONE* 14:e0212851.

Gilbert PW. 1970. Studies on the anatomy, physiology, and behavior of sharks. Mote Technical Report No. A-1970b. In. Sarasota, Florida, USA: Mote Marine Laboratory.

Hart NS, Collin SP. 2015. Sharks senses and shark repellents. *Integrative Zoology* 10:38-64.

Huveneers C, Rogers PJ, Semmens JM, Beckmann C, Kock AA, Page B, Goldsworthy SD. 2013. Effects of an electric field on white sharks: *in situ* testing of an electric deterrent. *PLoS ONE* 8:e62730.

Huveneers C, Whitmarsh S, Thiele M, Meyer L, Fox A, Bradshaw CJA. 2018. Effectiveness of five personal shark-bite deterrents for surfers. *Peerj* 6:5554.

Kajiura SM, Fitzgerald TP. 2009. Response of juvenile scalloped hammerhead sharks to electric stimuli. *Zoology* 112:241-250.

Kajiura SM, Holland KN. 2002. Electroreception in juvenile scalloped hammerhead and sandbar sharks. *Journal of Experimental Biology* 205:3609-3621.

Kalmijn AJ. 1982. Electric and magnetic field detection in elasmobranch fishes. *Science* 218:916-918.

Kalmijn AJ. 1971. The electric sense of sharks and rays. *Journal of Experimental Biology* 55:371-383.

Kempster RM, Egeberg CA, Hart NS, Ryan L, Chapuis L, Kerr CC, Schmidt C, Huveneers C, Gennari E, Yopak KE, et al. 2016. How close is too close? The effect of a non-lethal electric shark deterrent on white shark behaviour. *PLoS ONE* 11:e0157717.

Krogh M, Reid D. 1996. Bycatch in the protective shark meshing programme off south-eastern New South Wales, Australia. *Biological Conservation* 77:219-226.

Lamarque P. 1990. Electrophysiology of fish in electric fields. In: Cowx IG, Lamarque P, editors. Fishing with Electricity. Oxford: Blackwell Scientific. p. 4-33.

Lu J, Fishman HM. 1994. Interaction of apical and basal membrane ion channels underlies electroreception in ampullary epithelia of skates. *Biophysical Journal* 67:1525-1533.

Marcotte MM, Lowe CG. 2008. Behavioral responses of two species of sharks to pulsed, direct current electrical fields: Testing a potential shark deterrent. *Mar Technol Soc J* 42:53-61.

Murray RW. 1962. The response of the ampullae of Lorenzini of elasmobranchs to electrical stimulation. *Journal of Experimental Biology* 39:119-128.

Myers RA, Baum JK, Shepherd TD, Powers SP, Peterson CH. 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. *Science* 315:1846-1850.

Neiffer DL, Stamper MA. 2009. Fish sedation, analgesia, anesthesia, and euthanasia: considerations, methods, and types of drugs. *Institute for Laboratory Animal Research Journal* 50:343-360.

Peters RC, Evers HP. 1985. Frequency selectivity in the ampullary system of an elasmobranch fish (*Scyliorhinus canicula*). *Journal of Experimental Biology* 118:99-109.

Platt CJ, Bullock TH, Czéh G, Kovačević N, Konjević D, Gojković M. 1974. Comparison of electroreceptor, mechanoreceptor and optic evoked potentials in the brain of some rays and sharks. *Journal of Comparative Physiology* 95:323-355.

Ryan LA, Meeuwig JJ, Hemmi JM, Collin SP, Hart NS. 2015. It is not just size that matters: shark cruising speeds are species-specific. *Mar Biol* 162:1307-1318.

Sharber NG, Black JS. 1999. Epilepsy as a unifying principle in electrofishing theory: A proposal. *Trans. Am. Fish. Soc.* 128:666-671.

Smit CF, Peddemors V. 2003. Estimating the probability of a shark attack when using an electric repellent. *South African Statistical Journal* 37:59-78.

Smith ED. 1974. Electro-physiology of the electrical shark-repellant. *Transactions of the South African Institute of Electrical Engineers* 65:166-181.

Tricas TC, New JG. 1997. Sensitivity and response dynamics of elasmobranch electrosensory primary afferent neurons to near threshold fields. *J Comp Physiol A* 182:89-101.

West JG. 2011. Changing patterns of shark attacks in Australian waters. *Marine and Freshwater Research* 62:744-754.