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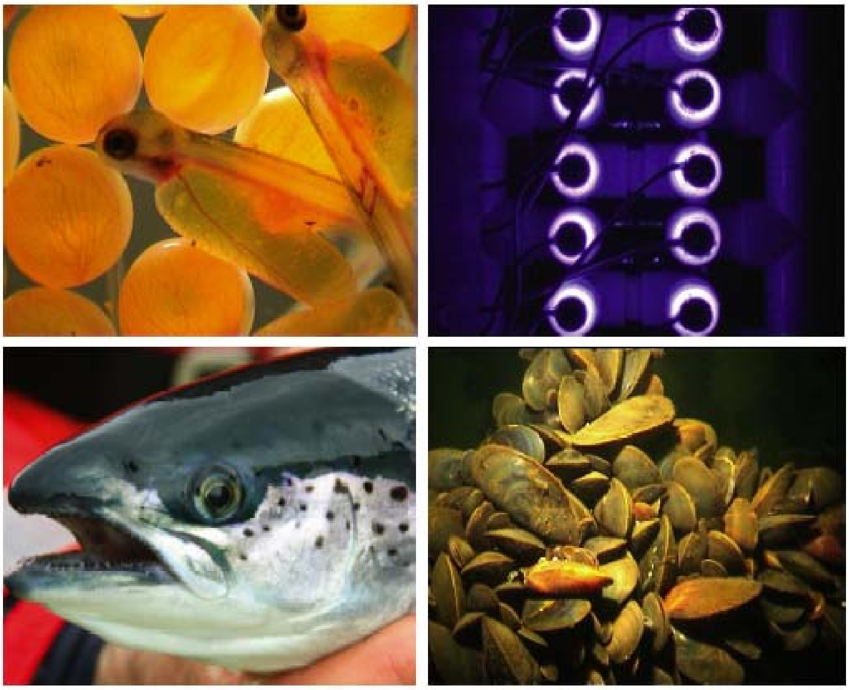
Behavioural Responses Of Seals To Pulsed, Low-Voltage Electric Fields In Sea Water (Preliminary Tests)



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Behavioural responses of seals to pulsed, low-voltage electric fields in sea water (preliminary tests)

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1. Introduction

Protecting caged fish from attacks by seals is a major concern for the salmon farming industry. To date this has relied on acoustic deterrents with questionable/variable degrees of success, barrier netting which is difficult to maintain or direct killing of seals which has only short term benefits in terms of reduced predation and significant long term costs in terms of the public image of marine aquaculture. The industry therefore needs a system of net defence that is reliable, effective, easily maintained and operated and benign or at worst, non-lethal to seals.

Studies in fresh water appear to indicate that seals may respond to electric fields at strengths significantly lower than those which cause behavioural responses in salmonid fish. A useable freshwater deterrence system has been developed and tested in the US and Canada on both captive and wild, free ranging seals and sea lions with promising results (Forrest *et al* 2009).

In sea water very large electrical currents are needed to sustain an electrical field, so there is little chance that this fresh water approach would be practical in the marine environment. It should however be possible to produce local electric fields within a few centimetres of a net wall with deterrent capabilities that could eventually be developed into a system for preventing direct attacks on net cages. The field strength needed in this new situation are not known so it is not possible to assess whether such protection is practical nor how it might affect the fish behaviour.

SARF commissioned the Sea Mammal Research Unit to conduct an experimental study to investigate the sensitivity of seals to low voltage electric fields (12 to 36v) in sea water. The stated aim of the project was to provide basic biological information with which to assess the potential for developing a system for net defence. Here we report the results of a study using temporarily captive grey seals (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*). We present the results of a series of dose response trials in the captive animal facility at the Sea Mammal Research Unit to test the responses of grey and harbour seals to local electric fields in sea water.

2. Background

It has been shown that seals can be excluded from some freshwater systems by the use of electric fields in the water (Forrest et al 2009). These installations were operated in low conductivity water (25 to 250 uS/cm) yet still required substantial (kilowatt) power supplies. The specific details of the field strength, pulse shape and frequency used are not provided by the authors however it is clear that replication of the same approach in seawater would require large amounts of electrical power. This is because the electric field required to stimulate an organism is likely to reduce only slowly with increasing water conductivity (Lines et al 2004) while the power required to sustain an electric field in water increases in direct proportion to the water conductivity and water volume. The power (in Watts) required to sustain an electric field in a conductive medium can be calculated as:

$$\text{Power} = 0.001 \times \text{Volume} \times \text{Conductivity} \times (\text{Electric field})^2 \text{..............................equ 1}$$

where the water volume is in litres, water conductivity is in μS/cm and the electric field is in V/cm.

The electrical power requirement can also be calculated from the voltage difference between the electrodes and the resistance between the electrodes:

$$P = V_{rms}^2 / R \text{ .... equ 2}$$

where P is the power requirement in Watts, needed to sustain a rms potential difference of V_{rms} volts over a resistance R ohms.

Kennelly (1909) shows that the resistance between a pair of parallel, cylindrical conductors in a conductive medium can be calculated as:

$$R = 10000 \text{ ArcCosh}(D/d) / \pi C \text{ .... equ3}$$

Where R is the resistance in ohms between a pair of 1m long electrodes each with a diameter d, separated by a distance D in water of conductivity C μS/cm.

Sea water has a conductivity of 45000-60000 uS/cm - approximately 1000 times more conductive than the water used by Forrest *et al* (2009) so the power requirement to replicate the Forrest setups in sea water would be between 200 and 1000 times greater than that used in the original trials.

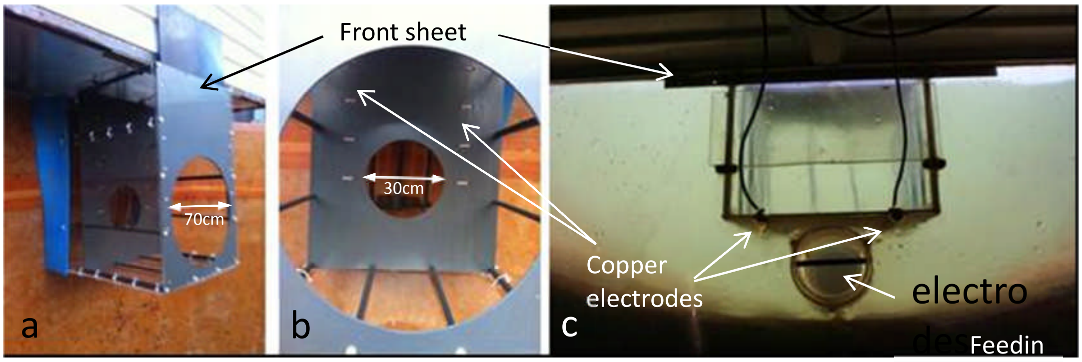
In a recent investigation Lines *et al* (2012) proposed a method to enable the subjective effect of electrical training collars on dogs to be ranked. As with the present trials, these collars generate a short sequence of high frequency voltage pulses. The investigation confirmed the widely held understanding that where the exposure duration and the impedance of the subject is constant, the apparent strength of the electrical stimulus can be approximately ranked according to the root mean square voltage (Vrms). It found however that a small improvement in the ranking could be obtained by the dividing the rms voltage by the voltage frequency raised to the power of 0.2.

While humans, dogs and seals are likely to have very large differences in their perceptions of electrical stimuli, there is little reason to assume that the ranking of stimuli will be substantially different.

3. Methods

3.1. Equipment

An experimental setup designed to expose seals to a controlled electric field was designed and built at the Sea Mammal Research Unit’s captive seal facility at the University of St Andrews. The apparatus delivers single food items to a clear Perspex feeding cylinder with an access port. The cylinder is simply rotated to open and close the access port and is hand operated by the experimenter. The feeding cylinder was fixed behind two opaque polyethylene sheets with access holes positioned so that seals can only gain access to the food by approaching from directly in front of the port (Fig 1).



Figure, 1 *the underwater feeding apparatus*. a) side , b) front and c) plan views of the feeding apparatus showing access holes designed to position the seal centrally between the two copper electrodes when entering the feeding tube.

Two cylindrical copper electrodes each 40 cm long and 1cm diameter were attached to the back of the rear polyethylene sheet. The electrodes were positioned vertically, 40 cm apart, on either side of the access hole on the back of the rear polyethylene sheet. They were positioned close to and on either side of the access port in the feeding cylinder. The seals therefore had to position their heads between the electrodes to gain access to food items. This design ensured that the animal's orientation was constant with respect to the test signal and ensured that the seal could not accidentally come into direct contact with the electrodes.

A low impedance voltage pulse generator was designed and built to generate a pulsed electric field in the vicinity of the entrance to the feeding tube. In its original configuration the device generated ten square wave pulses per second with variable voltages from 12 to 36V. Pulse lengths could be altered over a range of 10 to 1000 micro seconds. The polarity of the electrodes alternated between successive pulses to minimise electrolysis. Table 1 gives the range of voltages and pulse durations used in the experiments in 2011 and the RMS voltage generated at each setting.

The system was installed In September 2011 into the seal feeding set up. The feeding apparatus was fitted inside a hut suspended over the water in a large experimental swim tank (Fig 2). A clear Perspex panel with a mirrored surface over the feeder allowed the experimenter to maintain a constant watch of the feeding device throughout the trials allowing real time observation of the seal's behaviour. All experiments were videoed and response levels were assessed during video playback.

Figure, 2 *feeding apparatus installed in experimental pool. The feeding mechanism is suspended below the hut (just visible at the bottom of the hut) so that the experimenter is not visible to the seal. The seal was free to swim around the 6m diameter2m deep pool and could enter and leave the water at will.*

3.2. Experimental design.

The aim of these trials was to assess the levels at which seals reacted to the pulsed electric fields in order to identify a detection threshold and to examine the animals' responses to field strengths above this threshold.

Detecting such thresholds would usually be achieved by a series of trials where the range of signal amplitudes varied from well below to well above the expected detection threshold and the signal strength would be randomly assigned. Detection threshold would be based on some statistic such as 50% response..

However, because we intended to expose animals to electric fields and had little information to allow us to reliably predict the levels likely to cause effects the standard 50% response random signal approach could have exposed animals to unnecessarily powerful signals and was therefore deemed to be inappropriate. To avoid such problems we did not conduct randomised sequences of exposures. Instead we gradually increased the field strength, signal durations and pulse rates from very low levels that we expected to be undetectable.

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Seals were trained to approach the feeder and maintain station with their noses close to and usually in contact with the Perspex feeding tube. They were held for approximately 3 seconds before the tube was turned to give them access to a food reward, a single sprat (Sprattus sprattus) weighing approximately 10g. Each trial consisted of presentation of one fish. The seals were all trained to leave the feeder and return to the surface of the pool after each trial.

A single test comprised a series of 5 control trials with the device off followed by 5 trials with the electrodes energised. The electrodes were energised throughout the period of the 5 test trials, i.e. the power was applied after the seal left at the end of the 5th control trial and switched off after the 5th energised trial. This meant that when seals approached the feeder they were voluntarily swimming up a gradient of increasing electric field strength, ensuring that the electrodes were never energised when the seal was stationed in the feeding apparatus, therefore avoiding the possibility that seals could be subjected to higher field strengths than they were willing to tolerate.

Trials were carried out at a range of voltages 12, 18, 24, 30 and 36V and for each voltage at a series of different pulse durations of 10, 20, 50, 100, 200, 500 and 1000 micro sec (Table 1).

On the basis of reactions in initial trials, the seals' responses were classified into one of four categories:

1. No modification in behaviour from control
2. Holding back from the feeding port until it was opened to give access to food
3. Holding back from feeding port then exhibiting tremors or muscle twitch when passing through to access food
4. As above but tremors prevent seal from picking up food item.
5. Refusal to enter the feeding port.

The result of each individual trial was a score of 1 to 5 based on an assessment of the response as defined above. This scale is more or less arbitrary and the following descriptions of trends in the observed response levels contain no information on the relative magnitudes of response. The results should therefore be taken merely as indications of the direction of trend.

In 2011 two juvenile harbour seals were trained to use the feeding apparatus and tested at full range of voltages (12 to 36V) and signal durations (10 to 1000µs) but at only one pulse rate (10Hz).

In 2012 a total of four juvenile grey seals and one adult male harbour seal were trained to use the feeding apparatus and tested at full range of voltages (12 to 36V), signal durations (10 to 1000µs) and pulse rates (10 to 100Hz). Initial trials with slower pulse rates showed no response and were therefore not included in the full experiment.

The work was carried out under licence #60/4009 Animal (Scientific Procedures)Act 1986.

4. RESULTS

4.1 Signal strength

The voltage pulses of various durations used in the present trials were measured. Due to imperfect switching of the signals and losses due to the protective resistors in the signal generators, the rms voltages measured are not exactly the same as those that would result from perfect square pulses at the nominal supply voltages of 12, 18, 24, 30 and 36V. Comparison of measured and idealised values however show that the rms voltages are closely approximated by those of perfect square pulses at 91% of the nominal driving voltage. These values are given in Table 1.

RMS values were not measured directly at other pulse rates, but as the signals were discrete pulses and closely approximated to a square wave we could reliably estimate the RMS values at other pulse rates.

Table 1: *The rms voltage of pulse trains resulting from 10 Hz pulses for various nominal voltages and durations*

		Pulse duration (µS)						
		10	**20**	**50**	**100**	**200**	**500**	**1000**
Nominal Supply Voltage	**12**	0.11	0.15	0.24	0.35	0.49	0.77	1.09
	18	0.16	0.23	0.37	0.52	0.73	1.16	1.64
	24	0.22	0.31	0.49	0.69	0.98	1.54	2.18
	30	0.27	0.39	0.61	0.86	1.22	1.93	2.73
	36	0.33	0.46	0.73	1.04	1.47	2.32	3.28

4.2 Electric field mapping

The pulsed electric field was simulated using purpose written simulation package. The simulation in *figure 3* shows the predicted electric field with a rms voltage of 2.5V across the electrodes. Electrodes were modelled as 1cm diameter tubes positioned 40cm apart and fixed to the back of a nonconductive barrier with a 30cm hole centred between the electrodes. A series of ad-hoc measurements of field strength confirmed that the field generated in the trial was consistent with that shown here.

The resulting field was strongly constrained by the presence of the large flat insulating panel in front of the electrodes. This effectively reduced the field in front of the feeder to zero except for a small region directly in front of the entrance to the feeding tube. There was a relatively high field strength between and behind the electrodes and only a small extension of the field to the front of the entrance to the feeding tube.

The field map in figure 3 confirmed that seals entering the feeding device would not be exposed to any significant signal until they approached the feeding tube itself. The size and position of the entrance holes ensured that the seals always approached the feeding device from the same direction and were therefore exposed to similar electric fields on each approach.

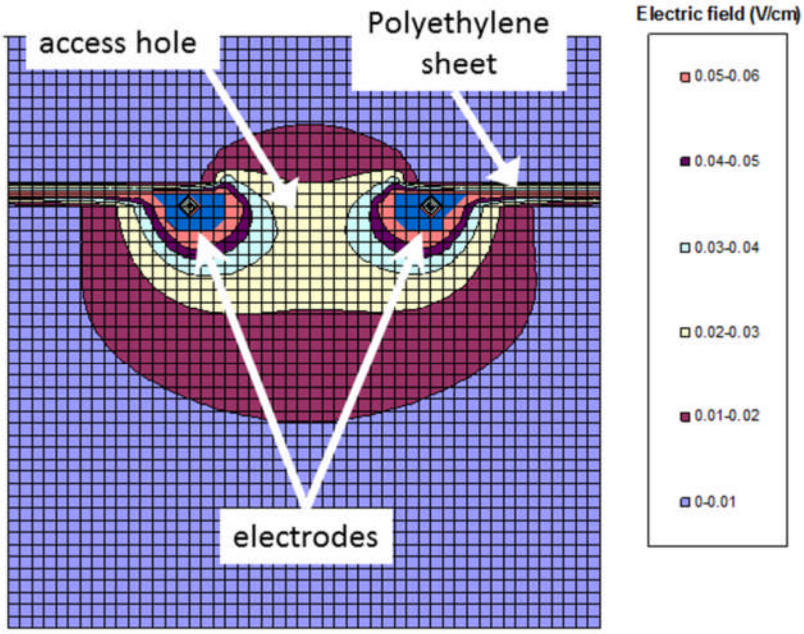

Figure 3. *Simulation results: the electric field used in the trials (plan view). The electrodes are black, and at the centre of the concentric circles. The plastic insulating sheet through which the seal inserts it head is also shown in black. The squares on the diagram are 2 cm x 2 cm and the electric field given in the key is in V/cm. The rms potential difference between the electrodes is 2.5V and the distance between them in 40 cm.*

4.3. Behavioural response trials

4.3.1 Juvenile harbour seal trials 2011.

Two juvenile harbour seals were tested with nominal voltages from 12 to 36 volts and signal durations of 10 to 1000µs at a pulse rate of 10Hz (*Table 2*).

Neither seal showed any signs of detecting or responding to the electric field at pulse durations of 10µs or 20µs at any voltage or to 50µs pulses at 12, 18, 24 or 36V. Both pups showed category 2 reactions in approximately 40% of trials at 30V.

The seals were clearly able to detect the fields at pulse durations of 100µs, showing category 2 responses in some trials at all voltages.   The proportion of trials eliciting a category 2 response increased from <3% at 12V up to 100% at 30 and 36V. The seals responded to these low field strengths by pulling back slightly from the tube and holding station a few centimetres from the tube until it was opened. They were still willing to move further into the field in order to enter the tube to take a fish on each trial.

Intensity of response increased with both voltage and pulse duration (figure 4). Both seals reacted in all trials with pulse durations of 200µs or greater except for 200µs at 12V where there was no detectable response in 44% of trials. The proportion of category 3 responses increased with both voltage and pulse duration (Table 2).

At pulse durations of 200µs to 1000µs the animals showed category 3 responses exhibiting substantial muscle tremors in some trials at all voltages. However, as with the category 2 reactions, they were still willing to move further into the field in order to enter the tube to take the food items.

The direct testing of responses of harbour seal juveniles was carried out over a three week period in late 2011. The trials were completed at one pulse rate (10Hz), but during additional calibration and field mapping work the electric field generator system suffered a component failure. No further trials were conducted with the harbour seals and both seals were successfully released back to the wild after veterinary inspection.

Table 2. Classification of harbour seal pup responses to different signal durations and nominal voltages. Data are pooled for the two seals. Numbers represent the number of trials in each of three categories; see text for definitions.

Nominal voltages			pulse duration (micro seconds)						
			10	**20**	**50**	**100**	**200**	**500**	**1000**
12	**RMS volts***		**0.102**	**0.152**	**0.247**	**0.353**	**0.503**	**0.794**	**1.124**
	Response	**1**	20	20	20	35	18		
		2				1	23	29	2
		3						1	8
18	**RMS volts**								
	Response	**1**	10	15	29	16			
		2				10	25		
		3					1	3	
24	**RMS volts**		**0.198**	**0.299**	**0.491**	**0.698**	**0.997**	**1.575**	**2.233**
	Response	**1**	20	25	26	3			
		2				32	25	4	1**
		3					5	11	9
30	**RMS volts**								
	Response	**1**	19	25	22				
		2			14	29	5	1	
		3					9	6	
36	**RMS volts**		**0.282**	**0.435**	**0.721**	**1.036**	**1.469**	**2.328**	**3.287**
	Response	**1**	10	10	10				
		2				10	2		
		3					6		

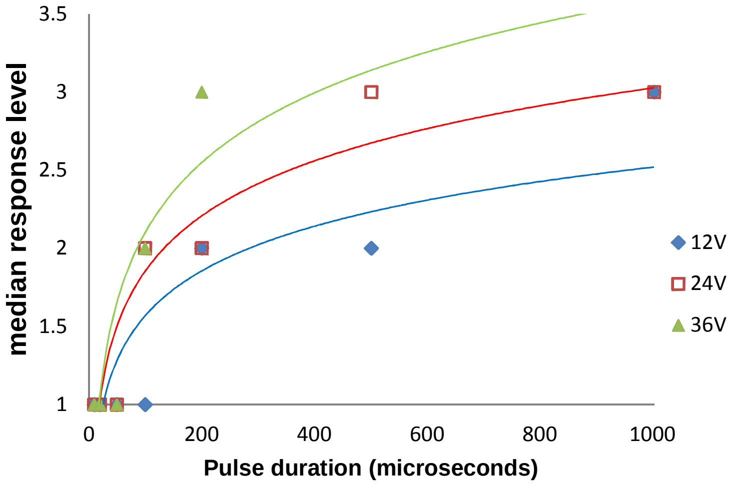

Figure 4. Median response level as a function of pulse duration. Values are medians of the category scores for the 2 harbour seal pups as described above at a pulse repetition rate of 10Hz. The lines are simple logarithmic fits, they have no statistical validity and are shown simply as a visual guide to show the general patterns in the different data sets. blue=12V, red=24V, green=36V

4.3.2 Juvenile grey seal trials 2012

The system was repaired and modified to include an increased range of stimuli. In addition to variation in voltage and pulse duration, the improved system included a range of pulse rates from 2 to 100Hz.

In early December 2011 four weaned grey seal pups were caught on the breeding colony at the Isle of May. They spent December acclimatising to the captive facility and had all begun feeding by late December allowing basic training to start.

The four juvenile grey seals were tested with nominal voltages of 12, 24 and 36 volts, signal durations of 10 to 1000µs and at pulse rates of 10Hz, 50Hz and 100Hz. The number of voltages and pulse rates tested with the four seals was limited by the amount of time available for experiments, but covered the whole useful range of options.

Seal responses were again assessed by reviewing video recordings of these trials.

As with the harbour seal juveniles, the grey seals showed no response to signals of 10µs or 20µs at any voltage and showed a pattern of increasing response level with increase in voltage and pulse durations above 20µs (Figure 5 and tables 3 & 4). There also appears to be an increase in response level with increased pulse rate at any particular pulse duration and voltage. All seals showed category 5 responses (refusal to enter the feeder) at signal durations of 200µs and above at 36V and 50Hz (Appendix 1).

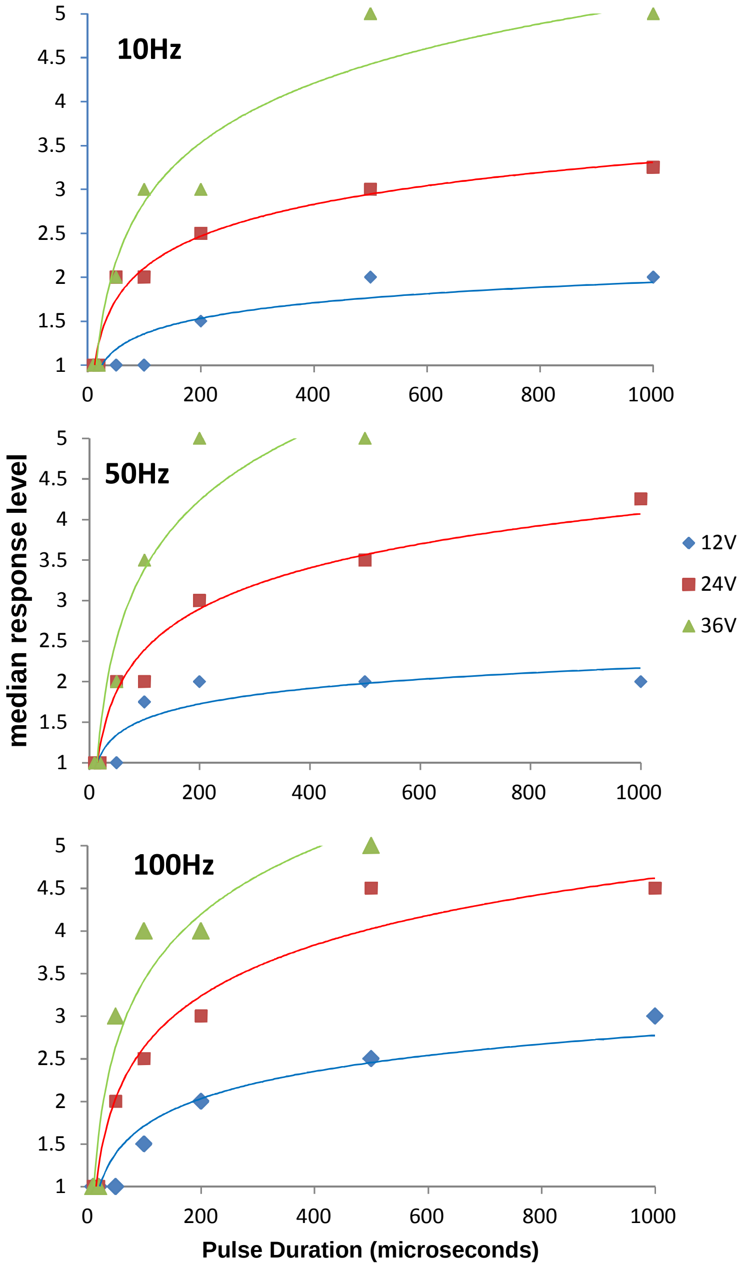

Figure 5. Median response level against pulse duration for 4 grey seal pups. The three plots represent three different pulse rates and the lines on each represent the different nominal voltages. The lines are simple logarithmic fits that have no statistical validity and are shown simply as a visual guide to the general patterns in the data. blue=12V, red=24V, green=36V

a.	12V			24V			36V		
	10Hz	50Hz	100Hz	10Hz	50Hz	100Hz	10Hz	50Hz	100Hz
10µs	1	1	1	1	1	1	1	1	1
20µs	1	1	1	1	1	1	1	1	1
50µs	1	1	1	2	2	2	2	2	3
100µs	1	1.75	1.5	2	2	2.5	3	3.5	4
200µs	1.5	2	2	2.5	3	3	3	5	4
500µs	2	2	2.5	3	3.5	4.5	5	5	5
1000µs	2	2	3	3.25	4.25	4.5	5		

b.	10Hz			50Hz			100Hz		
	12V	24V	36V	12V	24V	36V	12V	24V	36V
10µs	1	1	1	1	1	1	1	1	1
20µs	1	1	1	1	1	1	1	1	1
50µs	1	2	2	1	2	2	1	2	3
100µs	1	2	3	1.75	2	3.5	1.5	2.5	4
200µs	1.5	2.5	3	2	3	5	2	3	4
500µs	2	3	5	2	3.5	5	2.5	4.5	5
1000µs	2	3.25	5	2	4.25		3	4.5	

Table 3. Classification of greyseal pup responses to different signal durations, nominal voltages and pulse rates. Data are pooled for the four seals and presented as averages of the median values for each seal. Table 3a presents the data grouped by voltage and table 3b presents the data grouped by pulse rate.

Response level clearly responded to some combination of pulse duration, signal amplitude (voltage) and pulse rate, each of which is related to the amount of energy put into the water. Because the pulse generator produced approximately square wave signals with alternating polarities and relatively low duty cycles (maximum duty cycle was 10% with a pulse duration of 1000µs at a repetition rate of 100Hz), the RMS (Root Mean Square) voltage provides a convenient and appropriate proxy for the signal strength as perceived by the seals.

Plots of median response level against RMS voltage showed similar patterns for all four seals (figure 6) so the data were pooled and presented as the averages of the medians for the individual seals. These pooled results are presented in table 3.

In all four seals there is a clear pattern of increased response level with increased RMS voltage. All four showed some refusal at RMS values above 3V.

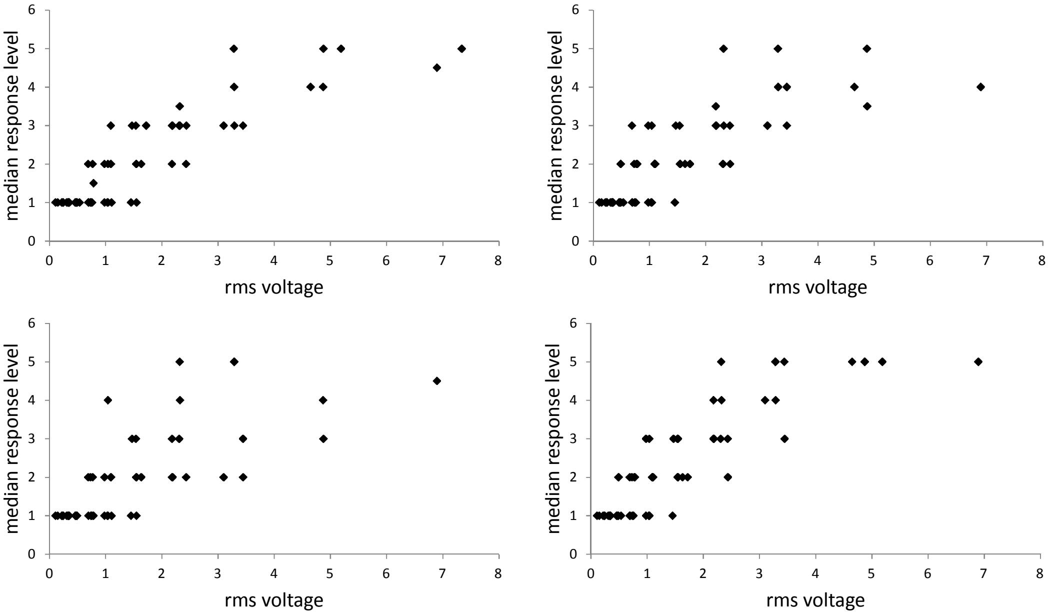

Figure 6. Median response level against RMS voltage for 4 grey seal pups.

4.3.3. Adult harbour seal trials 2012

In April 2012 an adult male harbour seal was caught at a haulout site in the Eden estuary. After acclimatization and training he was tested with nominal voltages of 12, 24 and 36 volts, signal durations of 10 to 1000µs and at pulse rates of 10Hz, 50Hz and 100Hz.   The number of voltages and pulse rates tested with the adult seal was limited by the amount of time available for experiments, and he was not tested at the highest signal duration values because he showed either category 4 or category 5 responses to lower values (Table 4).

Voltage and pulse frequency combinations

pulse duration (microseconds)	12 V			24 V			36 V		
	10 Hz	**50 Hz**	**100 Hz**	**10 Hz**	**50 Hz**	**100 Hz**	**10 Hz**	**50 Hz**	**100 Hz**
10	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1
50	1	1	1	2	2	2	2	4	4.5
100	1	2	1	3	4	4	3	5	5
200	2	2	2	4	5	5	4		
500	3	4	4						
1000	4	4							

Table 4. Classification of and adult male harbour seal's responses to different signal durations, nominal voltages and pulse rates.

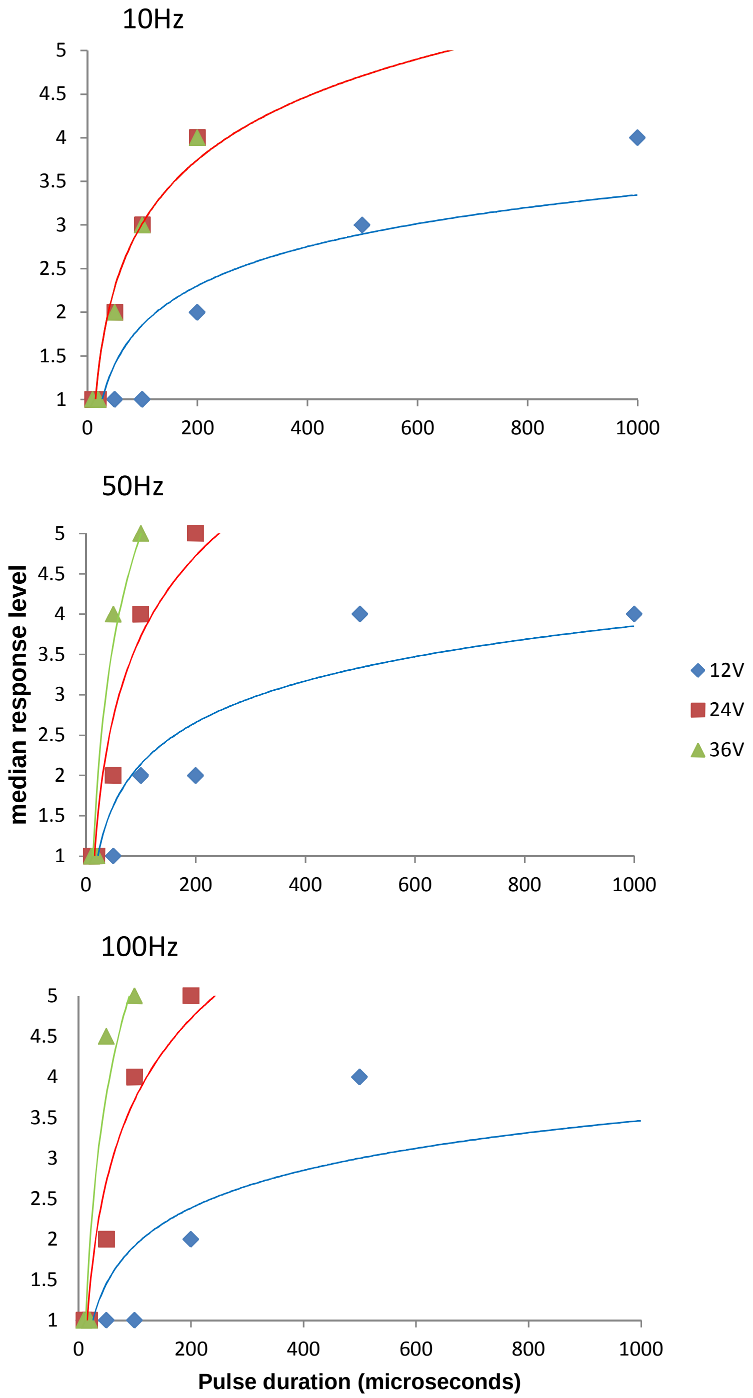

Figure 7 Median response level as a function of pulse duration for an adult male harbour. The three plots represent three different pulse rates. The lines are simple logarithmic fits, they have no statistical validity and are shown simply as a visual guide to show the general patterns in the different data sets

As with both the harbour and grey seal juveniles, the adult male harbour seal showed no response to signals of 10µs or 20µs at any voltage and showed a pattern of increasing response level with increase in voltage and pulse durations (Figure 7 and table 4). There also appears to be an increase in response level with increased pulse rate at any particular pulse duration and voltage.

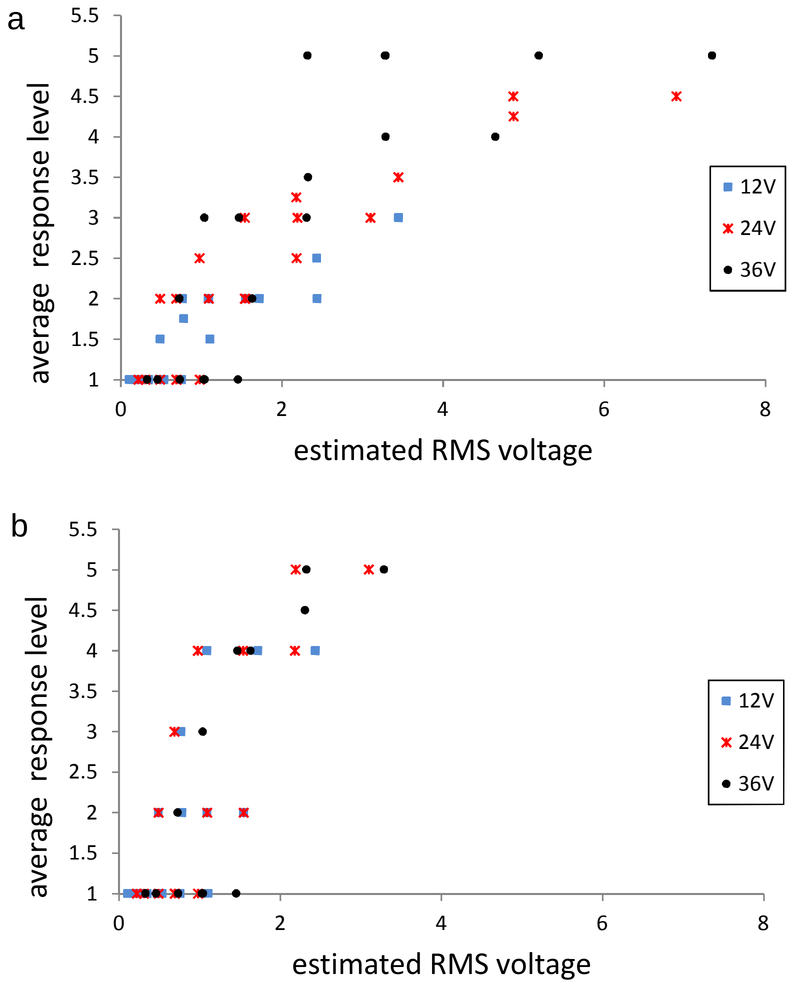

Figure 8. median response level as a function of RMS voltage: a) for four juvenile grey seals and b) for one adult male harbour seal. Grey seals were tested at the full range of pulse durations and voltages and pulse rates. The adult male harbour seal tested at a restricted and lower range of values as he showed strong responses or refusal at lower values than seen in the grey seal juveniles.

The adult harbour seal showed category 5 responses (refusal to enter the feeder) at signal durations of 100µs at 36V and 50 and 100Hz, and at signal durations of 200µs at 24V and 50 and 100Hz. This response level occurred at one step lower in terms of signal duration than was observed for juvenile grey seals.

5. Discussion

The trials have clearly shown that both seal species are able to detect low voltage pulsed electric fields. There is also strong evidence that the level of response varies in response to changes in some combination of pulse length, amplitude and repetition rate.

None of the seals showed any signs of detecting or responding to the electric field at short pulse durations of 10 or 20µs.

All seven seals tested have shown clear aversion responses, holding back from signals at higher pulse durations and voltages especially at the higher pulse rates. In most cases they have appeared willing to push past fields that cause mild muscle tremors or head shaking, but in the cases of grey seal pups and the adult harbour seal, when tested at higher pulse rates there was clear evidence of avoidance with seals refusing to push through the field.

In all cases these reactions were transitory in that all seals continued to use the feeding system after their refusals. In all cases seals returned to use the feeder during the same experimental session. After refusal there were indications that seals were more cautious in their approach on the next trial, but thereafter they returned to the device as usual. To date we have seen no clear sign of either sensitisation or habituation, but the trials conducted so far have had limited power to detect either.

In all cases the extent of the electric field or at least the extent of the effect zone was small. At the higher voltages, pulse lengths and pulse rates the seals pulled back from the entrance to the feeder where the field was most intense. However, even at the highest settings the seals usually stayed inside the feeder and held station within 30cm of the entrance.

The results show a clustering of data consistent with the hypothesis that rms voltage can be used as an indicator of stimulus strength and that the quantity calculated as rms voltage divided by frequency^0.2 provides a slightly more consistent indicator of stimulus strength. (Lines *et al* 2012).

The results suggest that in the experimental setting an rms potential difference of between 6 and 12 V is needed to deter juvenile grey seals from taking food, and an rms potential difference of between 2.5 and 5 V is needed to deter the adult harbour seal. This difference may be a function of the size of his head, as there would be a greater potential difference across his head than across the smaller pups' heads. Alternatively it could be that the adult seal is more risk sensitive and less willing to tolerate the unusual stimulus. We do not know whether this is related to age.

Figure 3 shows that the rms voltages applied to the electrodes and the resulting electric field in the water. Because of the geometry of this particular setup, the electric field at the centre of the seal access hole in V/cm is numerically equal to 1% of the voltage applied to the electrodes, thus an rms voltage of 6 V, which appears sufficient to deter most of the seals, results in an electric field of 0.06V/cm at the centre of the access hole. It is not clear however whether it is this electric field which is most relevant to the behaviour of the seals.

It could be that the seals penetrate the electric field until the voltage across their head reaches a certain level. The simulation shows the maximum voltage difference that can occur across a seal's head which is 10 cm wide as it feeds is 16% of the electrode potential difference if the head is in the centre of the field. The trial results might therefore indicate that a potential difference of 1 V (ie 0.16*6) across the seal head is required to deter most of the seals. The predictions are summarized in table 5.

	RMS Voltage across trial electrodes	Electric field at centre	Voltage difference over 10 cm
Adult. (High estimate)	5 V	0.05 V/cm	0.8 V
Adult. (Low estimate)	2.5 V	0.025 V/cm	0.4 V
Juvenile. (High estimate)	12 V	0.12 V/cm	2 V
Juvenile. (Low estimate)	6 V	0.06 V/cm	1 V

Table 5 showing possible electrical parameters required to deter seals based on the two assumptions identified in the text.

6. Implications of these finding for sea cage protection

There are at least two possible approaches to achieving this electric field: either the use of alternating polarity electrodes closely spaced around the sea cage (for example woven into the netting), or unipolar electrodes in the sea cage with the complimentary pole located on the cage anchorage ropes or elsewhere.

6.1. Alternating polarity electrodes.

These could comprise a series of vertical or horizontal conductors in a sea cage net. They should be relatively close together – perhaps 100 or 150 mm apart so that the electric field does not penetrate very far out of the plane of the net, since this would increase the volume of water being powered and hence the power demand. With closely spaced electrodes, an attacking seal would be very close to, or in contact with at least one of these conductors, so the electric field it would be subjected to could be higher than exists in the water at the centre of the electrodes. These pairs of conductors would be briefly but periodically energised and during the off time other similar pairs would be energised, thus the total volume of water sustaining an electric field at any one time would be reduced.

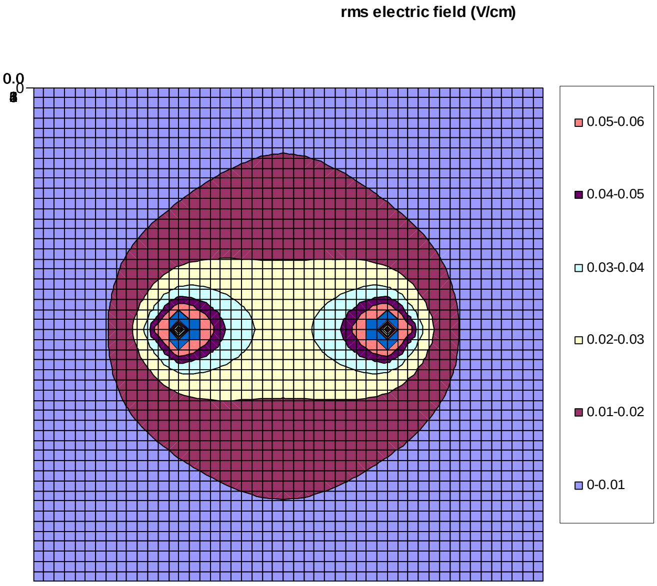

Figure 9. Simulation results: plan view of the electric field developed between two parallel vertical conductors 10 cm apart with a voltage difference of 0.5 volts rms between the conductors giving a nominal electric field of 0.05 v/cm. The squares are each 5mm x 5 mm. The electric field given in the key is in V/cm.

Figure 9 shows a simulation of the electric field generated between a pair of parallel conductors 10 cm apart with a potential difference of 0.5 volts rms. The minimum electric field at the mid point between these electrodes is 0.025 V/cm ie 5% of the numerical value of the potential difference. Reference to Table 5 suggests therefore that the potential difference between these conductors needed to deter seals will be between 0.4 and 1V for adult seals and between 1 and 2.4 V for juveniles.

The resistance between 1 m lengths of these two conductors in sea water is 0.25 Ω and this arrangement would protect and area of 0.2 m^2. Power requirements (calculated as V^2/R) therefore are from 3.2, 20 or 115 W/m^2 depending of the assumptions. A 20 x 20 m sea cage 8 m deep has an area of approximately 1000 m^2, so would require somewhere between 3.2 and 20 kW to protect the whole net simultaneously against adult attack and between 20 and 115 kW to protect the net against juvenile attack. It may however be that only a small proportion of the net needs to be protected at any one time. If a seal attack takes 5 seconds and a half second exposure is enough to deter the seal than total power requirements are reduced by a factor of 10. Further reduction in power requirement could be achieved by making the system responsive to seal attacks and only switching on when required. Such an approach is already in use with acoustic deterrent devices such as the Ace Aquatec acoustic seal deterrent system.

6.2. Single polarity electrodes.

Single polarity electrodes could also be woven into the net with the complimentary electrode some distance from the net, mounted on, for example the cage anchorages. Potential advantages of this configuration include:

- the direction of the electric field: fish (and so perhaps seals) have been observed to be almost twice as sensitive to electric fields running along their bodies in comparison to electric field running across their bodies.
- the electric field will be predominantly outside of the sea cage extending towards the cage anchorage rather than symmetrical on each side of the net, Therefore attacking seals are exposed to more of the electric field and the fish in the cage are exposed to less.
- distortions of the net caused by tidal flow (etc) are less likely to cause the electrodes to touch each other and so prevent the generation of an electric field.

An additional programme of trials, similar to those detailed above, will be required to determine whether the conditions needed to deter seals can be generated with similar low voltage systems and similar levels of energy input.

7. Conclusion

The project has clearly demonstrated that seals can be prevented from entering a small area using low voltage, short duration pulsed electric fields. This method therefore has clear potential as a net defence method. Approximate power requirements have been given however these vary widely since power is determined by the square of the voltage difference. Improved predictions of the power requirement require an improved understanding of

- which parameters of the electric field control the response of the seal;
- the observed difference between the single adult and the juveniles tested;
- whether a single polarity electrode configuration is more efficient; and
- the responses of the seals to electric fields that are intermittent and the potential for longer term learned responses.

Proposed future work to test the effectiveness and practicality of such a system will include studies of:

- Electrical conditions need to deter seals using the single polarity electrode configuration.

- The behaviour of seals of different sizes and increased sample sizes to determine the extent of inter animal and size related variation in response level.
- The effects of different electrode geometries, e.g. trials using areas of netting with woven in electrodes of various pitches

8. References

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