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Pulse trawl fishing: characteristics of the electrical stimulation and the effect on behaviour and injuries of Atlantic cod (*Gadus morhua*)

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In the North Sea flatfish fishery, electric pulse trawls have been introduced to replace the conventional mechanical method. Pulse trawls reduce the fuel consumption, reduce adverse impact on the ecosystem but cause injuries in gadoids. We describe the design and electrical properties of pulse trawls currently in use and study the behavioural response and injuries in cod exposed to electrical pulses under controlled conditions. Pulse trawls operate at an average power of 0.7 kW m^{-1} beam length and a duty cycle of ~2%. The electric field is heterogeneous with highest field strength occurring close to the conductors. Cod were exposed to three different pulse types for a range of field strengths, frequencies, and duty cycles. Two size classes were tested representing cod that escape through the meshes (11–17 cm) and market-sized cod that are retained in the net (34–56 cm). Cod exposed to a field strength of $\geq$37 V m^{-1} responded by moderate-to-strong muscular contractions. Some of the large cod ($n = 260$) developed haemorrhages and fractures in the spine, and haemal and neural arches in the tail part of the body. The probability of injuries increased with field strength and decreased when frequency was increased from 100 to 180 Hz. None of the small cod ($n = 132$) were injured and all survived. The field strength at the lateral boundaries of the trawl was too low to inflict injuries in cod.

Keywords: beam trawl, behaviour, electrofishing, field strength, flatfish, injury, North sea, roundfish.

Introduction

In the 1960s, heavy beam trawls were introduced that quickly outcompeted the otter trawl as the most efficient gear in the fishery for sole (*Solea solea*) and plaice (*Pleuronectes platessa*) in the North Sea. The beam trawl allowed fishers to fix the horizontal net opening and deploy a larger number of tickler chains to chase sole out of the sediment into the net. The increase in the number of tickler chains in combination with an increase in towing speed resulted in an increase in catch efficiency (Daan, 1997; Rijnsdorp *et al.*, 2008). The downside of this development was an increase in fuel use, a high bycatch of undersized fish and adverse impacts on the seabed habitat and the benthic ecosystem (de Groot, 1984; Jennings and Kaiser, 1998; Poos *et al.*, 2013). For each kilogramme of fish landed, beam trawl fisheries use 3.5 l of fuel (Taal *et al.*, 2010) and may discard 0.9 kg of fish and 1.6 kg of benthic invertebrates and debris (van Beek, 1998).

In pulse trawls, the mechanical stimulation is replaced by electrical stimulation which invokes a cramp response during which the fish is immobilized until entering the net. In addition, sole bends in a U-shape making them easier to catch in a bottom trawl (van Stralen, 2005). Experiments on the use of electric stimulation in bottom trawls started in the 1960s to reduce the fuel consumption and adverse ecosystem impacts (Stewart, 1977; de Groot and Boonstra, 1970). Since then this technique evolved and is currently used in fisheries for flatfish, brown shrimp, and razor clams (van Stralen, 2005; Polet at al., 2005a,b; Murray *et al.*, 2016). The flatfish trawlers are fishing with a temporary exemption from the EU prohibition to use electric stimulation in fishing gear (EU, 1998). As the flatfish pulse trawl has a lower weight and is towed at a lower speed, fuel consumption is reduced by ~50%, and the bycatch of benthos and undersized fish is reduced by 38 and 56%, respectively (van Marlen *et al.* 2014). Depestele *et al.* (2016) showed that the electrodes of the pulse trawl penetrate less deep into the sediment. The introduction of pulse trawls raised concern about possible adverse effects (Soetaert *et al.*, 2015a). Spine fractures were reported in roundfish in both field and laboratory studies (van Marlen, *et al.*, 2007; de Haan *et al.*, 2008; ICES 2010, 2011). In a comparative fishing experiment, 4 of 45 cod and 1 of 47 whiting caught in pulse trawls had a spine fracture (van Marlen *et al.*, 2014). No irreversible lesions could be detected in ragworms and shrimps as a direct consequence of exposure to electric pulses administered in the laboratory (Soetaert *et al.*, 2015b).

To assess the consequences of a possible transition from a trawl fishery using mechanical stimulation to a trawl fishery using electrical stimulation, knowledge is required on the electrical characteristics of the pulse trawls, as well as on the effects of electrical stimulation on marine organisms and the ecosystem. The objective of this paper is to fill part of this knowledge gap. The paper falls into two parts. First, we describe the pulse gear and the electrical characteristics as measured in the lab and *in situ*. Second, we expose cod to a range of pulse parameters to study their response and injuries inflicted.

Pulse trawl characteristics

Two Dutch companies, Delmeco Group BV and HFK-Engineering BV, provide commercial pulse gears. By 1 January 2015, 11 vessels are equipped with Delmeco pulse gear and 71 vessels use the HFK system. A pulse gear comprises of a power supply, a pulse generator, an electric cable and winch, discharge modules in the beam (or wing), and an array of electrodes rigged between the beam (or wing) and the groundrope (Figure 1). Electrodes consist of cylindrical conductors and isolators. The design and dimensions vary by system and by ship. The conducting part of an electrode ranges between 26 and 40% of the total length, excluding the isolated section to the wing or beam (Table 1). The sequence of pulse discharges differs per manufacturer. Delmeco electrodes are activated pair wise, while HFK electrodes are activated in odd and even groups.

Both pulse systems generate a bipolar pulse with a conductor voltage between 45 and 60 V, a pulse frequency of 45–80 Hz, and a pulsewidth of 100–270 μs (Figure 2). In Delmeco-1, the bipolar pulses are evenly distributed in time (Figure 2a). In Delmeco-2 and HFK, the interval between the bipolar pulses is minor (Figure 2c and d). The active part of a single pulse period (duty cycle) is ~2% for all systems. The Delmeco pulse has exponential edges reflecting inductive couplings in the discharge circuit, in contrast to the HFK systems which have steeper pulse edges. In this paper, we refer to the maximum amplitude (peak) of the conductor voltage, conductor current, and field strength.

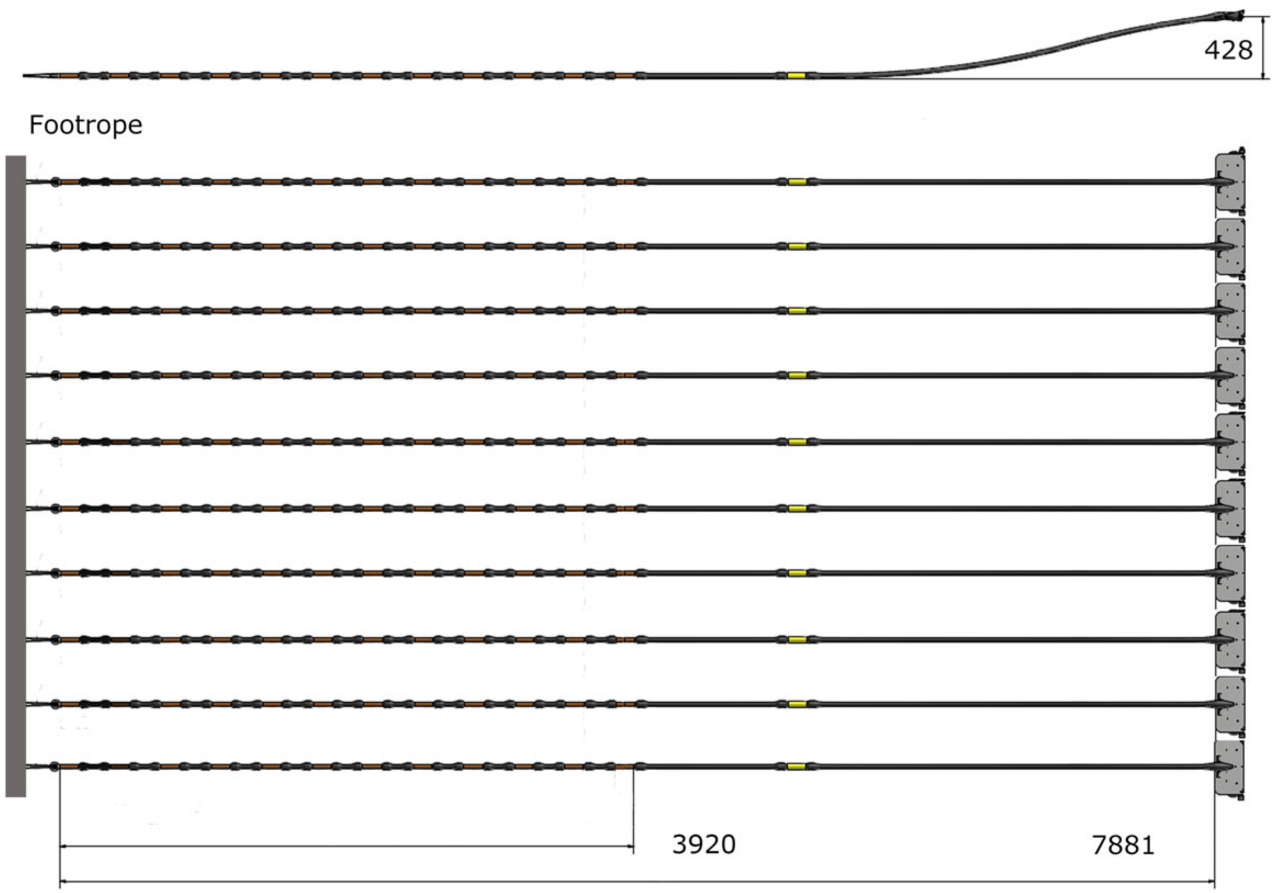

Figure 1. Rigging of a 4 m HFK pulse trawl. The top panel shows the side view with a vertical trawl opening of 0.43 m. The bottom panel shows the top view of 10 electrodes rigged between the wing and the groundrope. Each electrode consists of 12 conductor elements, evenly placed over a length of 3.92 m that are in contact with the seabed. An isolated joint is used to exchange electrodes.

Table 1. Overview of pulse trawl characteristics applied in the Dutch flatfish fishery.

Pulse concept	Vessel	Pulse type	Average power supplied per m beam width (kW)	Conductor voltage[a] (V)	Pulse frequency (Hz)	Pulsewidth[b] (µs)	Duty cycle (%)	Electrode: Number of electrodes	Electrode: Distance between electrodes (m)	Electrode: Number and dimensions (length × diameter, mm) of conductor elements
Beam trawlers ≤221 kW engine power, operating two 4.5 m wide beam trawls										
Delmeco-1	TH10	Bipolar	0.7	50	40	270	2.2	10 (1)	0.425	6 (180 × 26)
Beam trawlers >221 kW engine power, operating two 12 m wide beam trawls										
Delmeco-1	UK153	Bipolar	1	60	40	270	2.2	32	0.325	6 (180 × 26)
Delmeco-1	TX68	Bipolar	0.7	50	40	270	2.2	25	0.425	6 (180 × 26)
Delmeco-2	TX 19	Bipolar	0.7	50	80	130	2.1	25	0.425	6 (180 × 26)
HFK	OD17	Bipolar	0.6	45	45–80	100	0.9–1.6	28	0.415	2 (125 × 27) + 10 (125 × 33)

Delmeco-1 and HFK are the systems currently in use. Delmeco-UK153 specifies the settings of the first commercial trial in 2005. Delmeco-2 is exclusively used on-board TX19.
[a]All voltage ratings refer to the peak voltage measured over the positive part of the pulse (zero to peak).
[b]The pulse duration refers to the a single pulse period.

The alternating conductor and isolator elements generate a heterogeneous electric field. Field strength (V m^{-1}) was measured in a coordinate system with the *x-axis* perpendicular and the *y-axis* parallel with the electrode, and a vertical *z-axis*. The centre of the conductor is defined as the origin of the coordinate system ($X = 0$, $Y = 0$, $Z = 0$). Field strength was sampled in steps of 30 mm along seven longitudinal *y-axes* at 7 distances (*x-axis*) in and outside a pair of electrodes, and a number of vertical grid points between $Z = 0$ and $Z = 165$ mm.

The highest field strength was measured besides the centre of the conductor and decreased along the *x*- and the *y-axis* (Figure 3). Within the array of electrodes, field strength decreased along the *x-axis* with the square root of the distance to the conductor (Table 2). Outside the array of electrodes, field strength decreased at a faster rate than in the area between the electrodes. As the array of electrodes is fixed within 400 mm of the wings of the trawl, the field strength outside the trawl was estimated to be <17 V m^{-1} (95% CL limits: 13–21 V m^{-1}). In the vertical plane, field strength showed an exponential decrease with the distance from the conductor both along the horizontal *x-axis* and the vertical *z-axis* (Table 3). The slope along the vertical *z-axis* was steepest above the conductor but became more shallow when moving along the *x-axis* (Figure 3b).

To compare the field strength generated *in situ* to those applied in the tank experiment (see below), field strength was measured on-board of TH10 (Delmeco-1, 2 November 2011) and OD17 (HFK, 11 November 2011, maximum conductor voltage 45 V) with the fishing gear stabilized on the seabed at a drifting speed of 0.1–0.3 knots. A low-light underwater video camera was used to validate the measured positions and rigging performance. At the reference position for large cod ($X = 68$ mm, $Z = 45$ mm), field strength was 59 V m^{-1} and 69 V m^{-1} for Delmeco-1 and HFK, respectively. The field strength measured at the reference position for small cod ($X = 45$, $Z = 45$ mm) was 208 V m^{-1} for HFK. The voltage drop over the electrodes was minor (2–3 V).

Pulse exposure experiments

Both small and large-sized cod were exposed to electrical pulses. The small cod represent fish that may escape through the codend meshes of commercial trawls. The large cod represent the market-sized fish that are retained in the net. A total 39 experiments were conducted at Austevoll Research Station, three experiments between 29 October and 15 November 2008 and 36 experiments between 28 November and 14 December 2010 (Table 4). In each experiments, 10–20 cod were exposed. In addition, three control experiments were conducted in which 10–20 were handled but not exposed to the pulse stimulus. Each individual was tested once and sacrificed for autopsy. All experiments were carried out with approval of the Norwegian Animal Welfare Commission (2008—ID1230; 2010—ID2898).

At the start of the experiment, a fish was transferred from the holding tanks to a meshed cage of synthetic material. Large cod were positioned parallel with the conductor with the beak at the edge (Figure 4). Small cod were exposed both parallel and perpendicular to the conductor. All experiments applied a single exposure, except in 2008 and the first trial with small cod in 2010, when fish were exposed four times within 12–38 s and within 5 min for small and large cod, respectively. The exposure duration was 1 s which is close to the *in situ* exposure time of 1.36 s of a 3.5 m electrode towed at 2.57 m s^{-1} (5 knots).

In the experiments in 2008, Delmeco-1 was used with the pulse setting of the UK 153 (Table 1). In 2010, a range of pulse settings

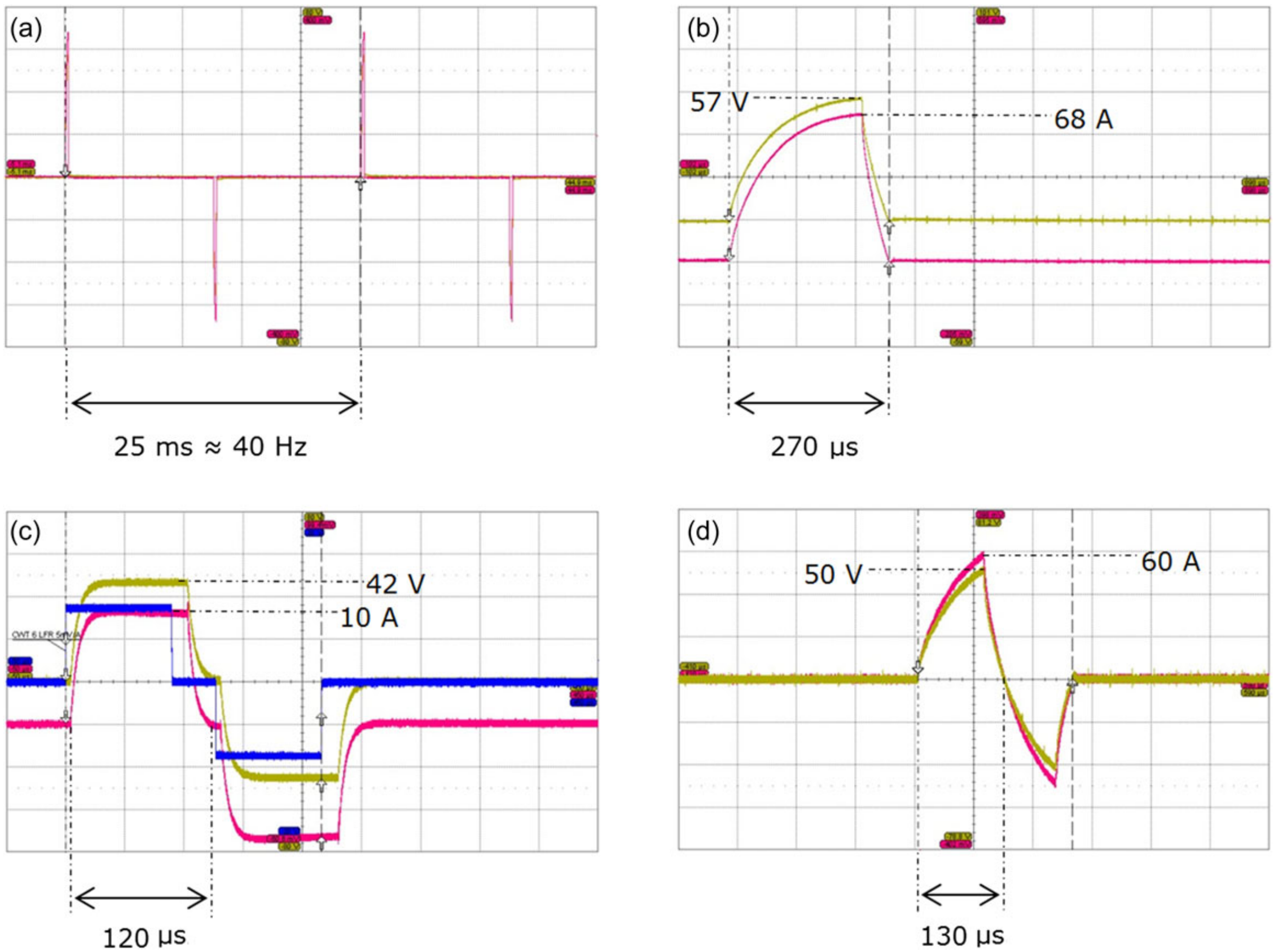

Figure 2. Conductor voltage (V) and conductor current (A) of the three commercial pulse types studied: Delmeco-1 (a and b), HFK (c), and Delmeco-2 (d). In (b) and (c), the conductor current was shifted by one division.

was tested for three commercial pulse concepts (Table 4). The electrodes consisted of a double pair of conductors separated by 0.6 m isolators (Delmeco-1 and -2) or a single pair of conductors (HFK).

Origin of the experimental cod and holding conditions

Cod were derived from the Austevoll research hatchery. The small fish ($n = 132$, 11–17 cm, 12–61 g) were from the hatch of 2010. The large fish were from the hatch of 2006 (2008 experiment: $n = 60$, 41–55 cm, 945–1953 g) and 2008 (2010 experiment: $n = 260$, 34–56 cm, 663–2295 g).

The research was conducted in an outdoor laboratory with three holding tanks and one experimental tank, each 3 m in diameter, and with a water height of 0.6 m. The small cod were transferred from the breeding tank 2 months before the start of the experiment. Large cod were transferred to a holding tank a week before the first experiment. Fish were fed daily. The seawater in the tanks was pumped from the adjacent fjord. The conditions during husbandry and experiments were stable (salinity: 34.8 ± 0.1 ppt; temperature: 7.5 ± 0.01°C). None of fish died after the transfer to the experimental tanks.

Observations

The behaviour was recorded as either a response or no-response to the electric stimulus. Directly after exposure the fish were released in the fourth tank for observation. Large cod tested in 2008 were observed for 15 d and feeding was recorded. After the observation period, fish were euthanized, their length and weight recorded and stored at −20°C for later post-mortem analysis. The number of cod in each experiment that developed a skin discolouration within 1 h after exposure was recorded. Four cod with skin discolouration that did not survive the exposures of 2008 were dissected directly after exposure (and not processed further) to relate the discolouration with the occurrence of injuries.

Haemorrhages ("haemor") were recorded by careful dissection of the fish after being de-frosted at room temperature (Figure 5c). The vertebral column with 1 cm surrounding musculature remaining on the lateral sides was radiographed to detect vertebral fractures. The fish exposed in 2008 were scored for fractures of the spine (denoted "vertebral"). In 2010, a more detailed analysis was conducted by also distinguishing fractures of the neural and haemal arches ("neural" and "haemal") (Figure 5b). All fractures of the arches had a clear rupture at the basis. Spine fractures involved fractured vertebrae and clearly ruptured intervertebral ligaments. Smaller dislocations between adjacent vertebrae were not recorded as an injury since the fish had been frozen and de-frosted, which may lead to slight dislocations of vertebrae. The location (i.e. vertebra number) of the fractures was recorded to study the fracture probability in the cervical (V1–2), abdominal (V3–19), caudal (V20–40), and ural (V41 and onwards) regions.

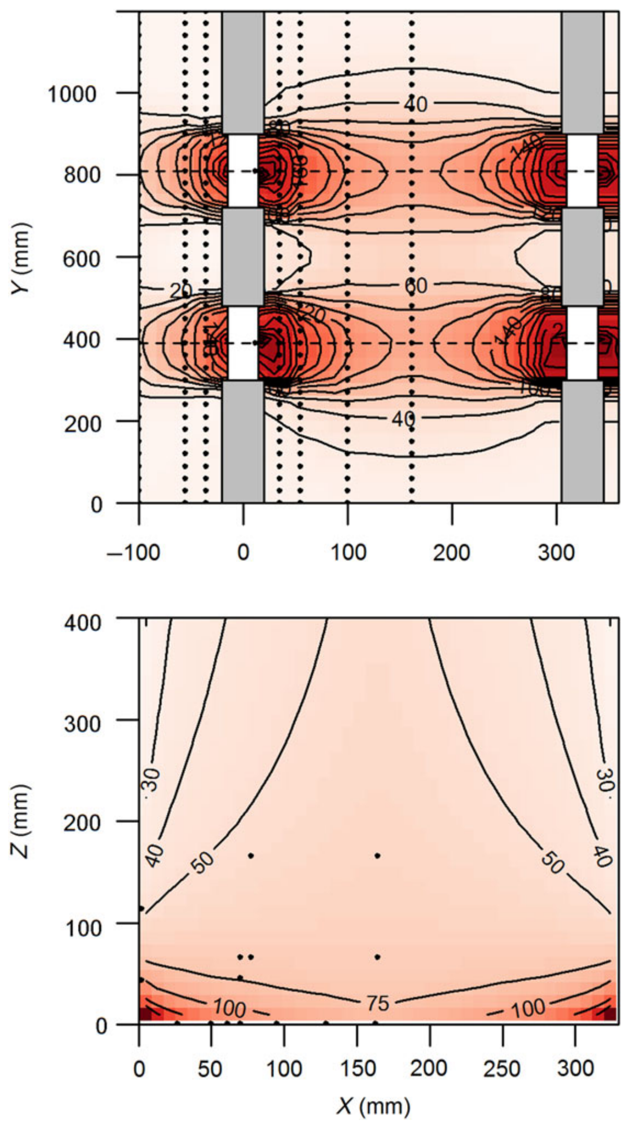

Figure 3. Contours of peak field strength (V m^{-1}) around a pair of Delmeco electrodes positioned at $X = 0$ mm and $X = 325$ mm. (a) The contours in the horizontal plane. The white parts show the conductors, grey parts show the isolators. The pattern on the left side of the electrode shows the decline in field strength outside the pair of electrodes. (b) The contours in the vertical plane with the headrope located at $Z = 430$ mm. The dashed lines in (a) show the location of the vertical plane depicted in (b). Locations of the measurements are indicated by black dots.

Statistical analysis

The response (R) of individual fish, scored as either having an injury or having no injury, was analysed as a function of body length and pulse parameters according the following generalized linear model:

$$R \sim \alpha + \beta_i X_i + \beta_j X_j + \beta_{ii} X_i X_j + \in,$$

where α is the intercept and X_i and X_j are explanatory variables (body length, field strength, frequency, duty cycle, and pulse type) and ε denotes the binomial distributed error term. The interaction term $X_i X_j$ tested for the possible differences in the effect of a pulse parameter for different fish sizes. Model selection was based on the AIC criterion starting with the full model. Analysis was done using R version 3.0.2 (R core team, 2013). None of the pulse parameters were strongly correlated ($r < 0.53$), except for pulse frequency and pulsewidth ($r = -0.77$).

Table 2. Parameters of the GLM model of the $\log_e$ transformed field strength (V m^{-1}) as a function of the $\log_e$ transformed distance (X, mm) to the nearest conductor between a pair of electrodes and outside a pair of electrodes.

	Estimate	SE	*p*
Between electrode pair			
Intercept	7.219	0.114	<0.001
Slope $\log_e X$	−0.516	0.027	<0.001
Outside electrode pair			
Intercept	8.253	0.242	<0.001
Slope $\log_e X$	−0.908	0.059	<0.001

Relationship refer to the measurements taken at the centre of the conductor ($Y = 0$, $Z = 0$) where peak field strengths occur.

Table 3. Parameters of the GLM model of the $\log_e$ transformed field strength (V m^{-1}) as a function of the $\log_e$ transformed distance (mm) to the nearest conductor along the horizontal (X) and the vertical (Z) axis between a pair of electrodes.

	Estimate	SE	*p*
Intercept	9.334	0.779	<0.001
Slope $\log_e X$	−0.735	0.186	<0.001
Slope $\log_e Z$	−1.058	0.158	<0.001
Slope $\log_e X \times \log_e Z$	0.152	0.037	<0.001

Relationship refer to the measurements taken at the centre of the conductor ($Y = 0$).

Results

Behavioural response

Except for the cod exposed to a field strength of 4 V m^{-1}, all cod showed a muscular contraction which immobilized them for the duration of the exposure. Small cod exposed for 1 s to a field strength between 212 and 370 V m^{-1} produced a muscular contraction with incidentally an epileptic seizure like response directly after the pulse extinguished. Within a minute, these fish recovered and returned to normal behaviour and responded to feeding. A stronger response, similar to electro-narcosis, occurred in 6 of the 20 small cod exposed to 4 stimuli of 1 s during a period of 12–38 s. These fish recovered within a minute and were kept alive over the weekend and resumed their normal feeding behaviour.

Large cod exposed to a field strength between 37 and 155 V m^{-1} showed a moderate-to-strong muscular contraction for the duration of the exposure (cramp response). After the pulse extinguished cod showed strong tail flapping and some showed epileptic seizure. Incidentally, a cod jumped out the experimental cage into the main basin. In the 2008 experiments, the behaviour was observed for a period of 15 days after exposure. All fish started feeding at the first offering of food ~36 h after exposure, although the feeding response was lower than before exposure. The appetite of fish exposed at 37 V m^{-1} increased during the observation period and was higher than the appetite of fish exposed at 4 V m^{-1} and "control" fish. Most of the fish exposed at 82 V m^{-1}, of which many developed vertebral fractures (see below), were passive and did not resume normal feeding.

Table 4. Overview of the exposure experiments, the number of cod used, and the range of pulse settings tested.

Trials (*n*)	Fish (*n*)	Pulse type	Frequency (Hz)	Pulsewidth (μs)	Duty cycle (%)	Electrode voltage (V)	Electrode current (A cm^{-1})	Field strength (V m^{-1})	Test position (*X*, *Z*, mm)
Large cod 2008 and 2010									
1	20	1[a]	40	270	2.16	57	1.92[b]	4	−413, −30
1	20	1[a]	40	270	2.16	57	1.92[b]	37	162.5, 165
1	20	1[a]	40	270	2.16	57	1.92[b]	82	75, 65
11	110	1	30.6–57.5	191–270	1.2–3.1	20–57	0.64–1.89[b]	37–103	68, 45
4	40	2	80	130	2.12	22–50	0.67–1.6[b]	n.a.	n.a.
11	110	3	30–180	80–270	1.26–2.88	40–60	0.64–0.96	57–87	68, 45
Small cod									
2	40	1	40	270	2.16	57	1.92	255	48, 0
1	20[c]	1	40	270	2.16	57	1.92	124–347	25–161, 0
1	20	2	80	130	2.08	50	1.61	n.a.	n.a.
3	30	3	30–180	80–270	1.26–2.88	60	0.64–0.96	212	48, 0
3	30[c]	3	30–180	80–270	1.26–2.88	60	0.64–0.96	76–370	25–161, 0

Pulse type refers to Delmeco-1 (type 1), Delmeco-2 (type 2), and HFK (type 3).
[a]Experiment 2008, exposed to a series of four stimuli.
[b]Current values of Delmeco 1 and Delmeco 2 were adjusted to the current of a single pair of conductors per centimetre length to enable comparing HFK results.
[c]Fish positioned perpendicular to the conductor.

Injuries

Part of the exposed cod showed a discolouration mark, and an occasional anal bleeding or haemorrhage of anal and caudal fins. Marks faded after euthanasia and were no longer visible when the fish was de-frozen for dissection. Marks varied between single bars, chevrons, or a fully discoloured tail (Figure 5a). Not all marks developed within 1 h after stimulation. In one experiment, one cod with a distinct discolouration mark directly after exposure was euthanized and the other nine were kept alive overnight. The next morning, two other cod showed a discolouration mark.

Marks co-occurred with internal injuries. Dissection of cod with marks showed a haemorrhage and a fracture of the spine in all four fish. Comparison of the number of cod with marks and haemorrhages in each experiment showed that the number of cod with a mark never exceeded the number of cod with haemorrhage or fracture. A mark developed in 62 cod immediately after exposure, whereas a haemorrhage was observed in 101 cod. The discrepancy is likely because not all marks develop within the 1 h observation period used in this study. One experiment showed that the number of cod with marks (3) matched the number of cod showing haemorrhages but did not match with the number of cod with a fracture (1). This suggests that a discolouration mark is directly related to the development of a haemorrhage.

None of the cod in the control experiments and none of the small cod became injured, while of 39% of the large cod exposed in 2010 and 45% of the large cod in 2008 showed either a vertebral fracture, a haemorrhage, or both (Table 5). All haemorrhages occurred at the location of the fracture, often in the cranial part of the tail region between vertebra V20 and V25 (Figure 6). The neural arch fractures occurred in a wider section of the vertebral column between vertebra V14 and V25. In four cod, haemorrhages were observed in the absence of a vertebral fracture.

The injury probability of large cod was analysed in relation to body size and the pulse parameters: frequency, field strength, duty cycle, and pulse type. The selected models for three injury classes explained between 12 and 4% of the variance. The parameter estimates of the selected models are given in Table 6. The probability of haemorrhages is significantly affected by field strength and to a lesser degree by frequency and duty cycle. No effect of pulse type was found. Length showed a significant interaction with frequency and duty cycle. The probability of vertebral fractures showed a similar relationship with field strength, frequency, and body size. The probability of a spine fracture was significantly related to field strength and body size. The probability of fractures was lower for the Delmeco-2 as compared with Delmeco-1 and HFK. For spine fractures, HFK showed a lower probability when compared with Delmeco-1, but this could be due to the effect of frequency, which was tested in a wider range for HFK.

Figure 7 shows the effects of pulse parameters and body size on the injury probabilities. The results are representative for the parameter setting of HFK and a body size of 50 cm. In general, the injury probability increased with the field strength and, to some degree, with an increase in duty cycle, and decreased with the pulse frequency. The injury probability tended to decrease with body size within the market-sized cod.

Discussion

Behavioural response

All large cod exposed to a field strength of at least 37 V m^{-1} responded to electrical stimulation and showed a cramp response. Small cod exposed to a stimulus of 1 s incidentally developed an epileptic seizure type of response. Despite the high field strength (>200 V m^{-1}) all fish quickly recovered and no aberrant behaviour was observed in fish that were kept alive for a few days.

Electro-narcosis ("stunning") occurred when small cod was exposed to four stimuli within a period of 12–38 s. This is a common observation in stunning experiments where the exposure duration is increased from 3–12 s in Atlantic herring, Atlantic salmon (*Salmo salar*), and pollock (*Pollachius virens*) exposed to a 50 Hz sinusoidal alternating current (AC) stimulus (Roth *et al.*, 2004; Nordgreen *et al.*, 2008).

Injuries

Our results suggest that a discolouration mark is directly related to the development of a haemorrhage after exposure to an electrical stimulus. Similar skin discolouration has been reported in rainbow trout (Horak and Klein, 1967; Holmes *et al.*, 1990; Lamarque, 1990; Fredenberg, 1992), although injured fish could also lack marks (Fredenberg, 1992). Sharber and Carothers (1988) showed that these external marks reflect severe internal lesions. Sharber and

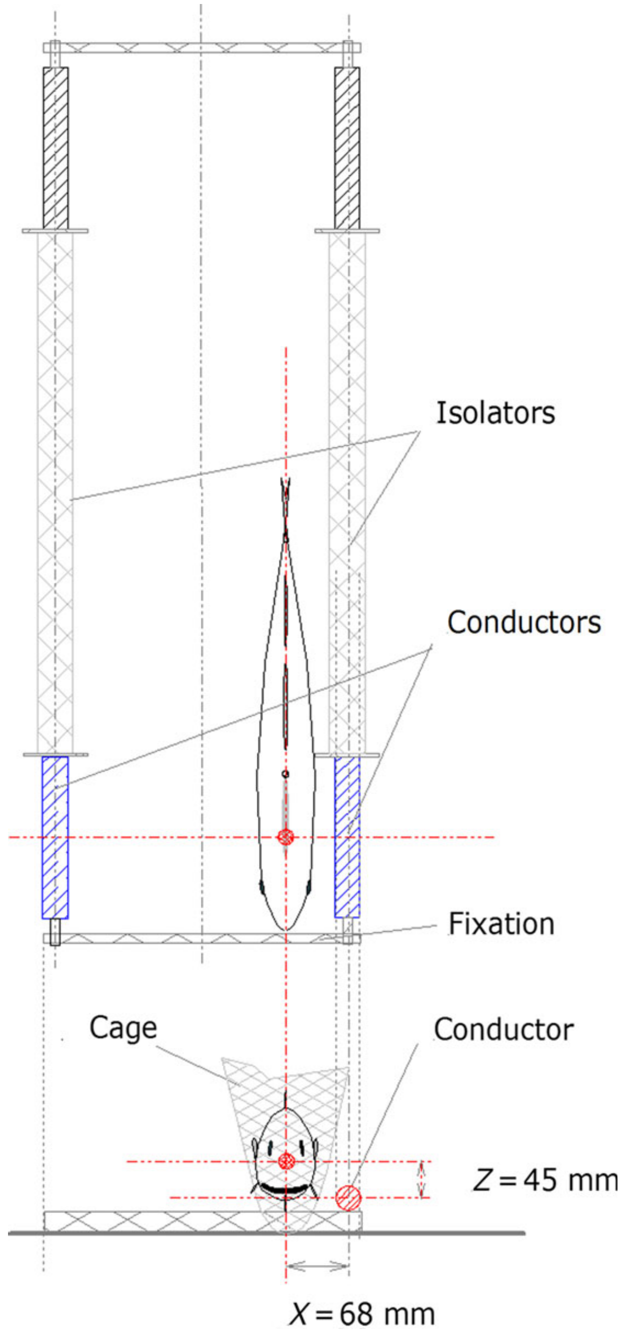

Figure 4. Position of a large cod relative to the Delmeco conductor when exposed to an electrical stimulus. The field strength reference was measured at the centre of the conductor $X = 68$ mm, $Y = 0$ mm, and $Z = 45$ mm.

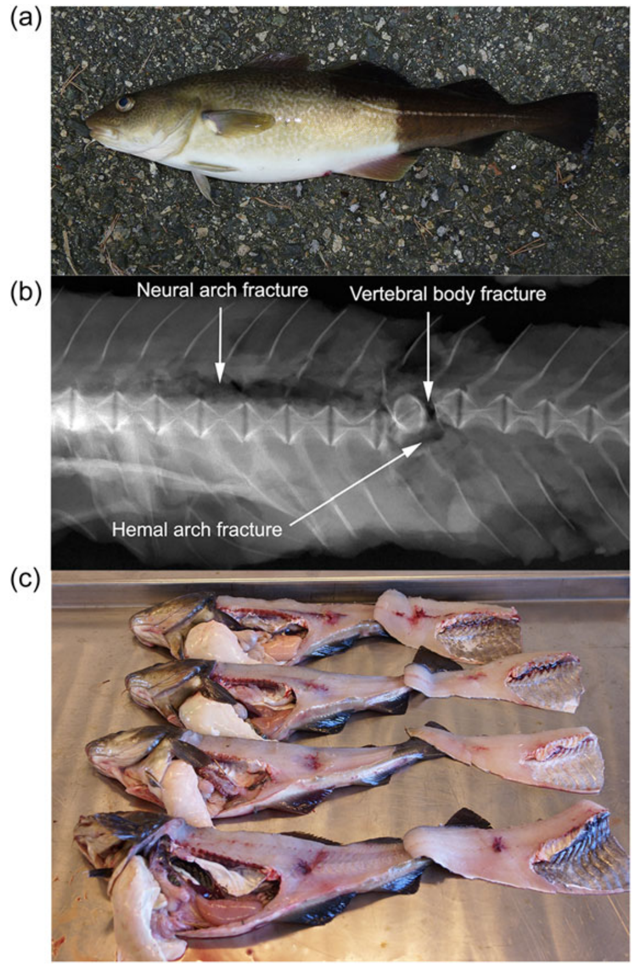

Figure 5. Injury types recorded in the experiments: (a) discolouration of the tail region; (b) fracture of the spine (vertebral body), neural and haemal arch; (c) haemorrhages observed in four cod showing discolouration.

Table 5. Frequency distribution of market-sized cod showing different combinations of haemorrhages and fractures.

	Number of fish	Percentage (%)
Combination of haemorrhages and fractures		
Haemorrhages only	4	2
Fracture + haemorrhage	97	37
No injuries	159	61
Total	260	
Combination of different type of fractures		
Spine	5	5
Haemal arch	17	18
Neural arch	18	19
Spine + neural arch	32	33
Spine + haemal arch	8	8
Neural + haemal arches	1	1
Spine + neural + haemal arches	16	16
Total	97	

Data of 2010 experiments.

Black (1999) suggested that discolourations are due to the dilation of skin melanophores, possibly as a result of sympathetic nerve damage or stimulation.

The injuries observed in cod exposed to an electrical stimulus are similar to the injuries observed in the pulse fisheries (van Marlen *et al.*, 2007, 2014; own observations). Haemal and spine injuries were located in the caudal region, while the neural injuries occurred in the abdominal and caudal regions. It is noteworthy that in the abdominal region, that is, exposed to the highest field strength, the number of fractures is lower than in the caudal region which is exposed to a much lower field strength. This indicates that the mechanical load imposed by the muscle contraction is largest in the

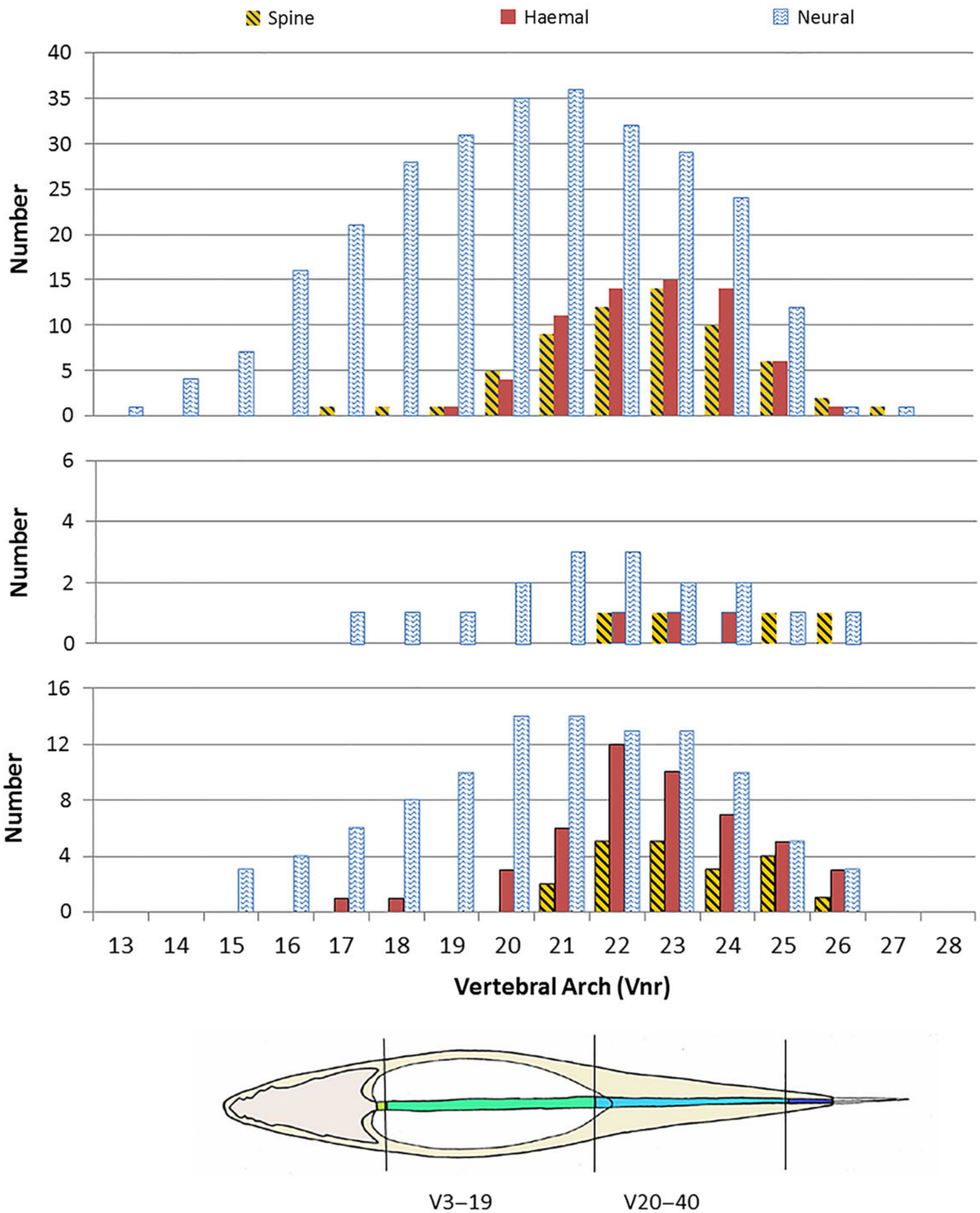

Figure 6. Location of the fractures in the spine, haemal, and neural arches of large cod exposed to (a) Delmeco-1, (b) Delmeco-2, (c) HFK. The cross-section of a cod shows the abdominal and caudal section of the vertebral column (based on Fjelldal *et al.*, 2013).

caudal region. This inference is in agreement with the observation that farmed cod develop lordosis in this region (Fjelldal *et al.*, 2009; Opstad *et al.*, 2013).

Vertebral fractures are not uncommon in fish exposed to electrical stimuli. Salmonids are reported to be highly sensitive to electric stimuli with 50% of the dissected fish showing vertebral injuries

Table 6. Parameter estimates of the injury probability (haemorrhages, fractures (all), and spine fracture) of market-sized cod from the preferred GLM model as a function of body size (cm) and pulse parameters (frequency (Hz), field strength (V m^{-1}), duty cycle (%), and pulse type (P1 = Delmeco-1, P2 = Delmeco-2, and P3 = HFK).

	Haemorrhages					**Fractures (all)**					**Spine fracture**				
	Estimate	**SE**	**z value**	**Pr(>|z|)**		**Estimate**	**SE**	**z value**	**Pr(>|z|)**		**Estimate**	**SE**	**z value**	**Pr(>|z|)**	
(Intercept)	15.34	8.99	1.71	0.088	.	2.12	1.92	1.10	0.270		1.63	2.14	0.76	0.447	
Length	−0.366	0.193	−1.90	0.058	.	−0.08	0.04	−2.15	0.031	*	−0.10	0.04	−2.23	0.026	*
Frequency	0.145	0.061	2.36	0.018	*	−0.01	0.01	−2.58	0.010	**					
Field strength	0.026	0.007	3.56	0.000	***	0.03	0.01	4.32	0.000	***	0.03	0.01	3.98	0.000	***
Duty cycle	−10.44	4.99	−2.09	0.036	*										
Length × Frequency	−0.004	0.001	−2.69	0.007	**										
Length × DutyCycle	0.234	0.107	2.19	0.028	*										
as.factor(PulseType)P2						−1.23	0.55	−2.22	0.026	*	−2.02	0.65	−3.09	0.002	**
as.factor(PulseType)P3						0.05	0.32	0.15	0.877		−0.75	0.34	−2.23	0.026	*

Data from 2008 experiments ("far and medium" exposure) and 2010 experiments.
Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

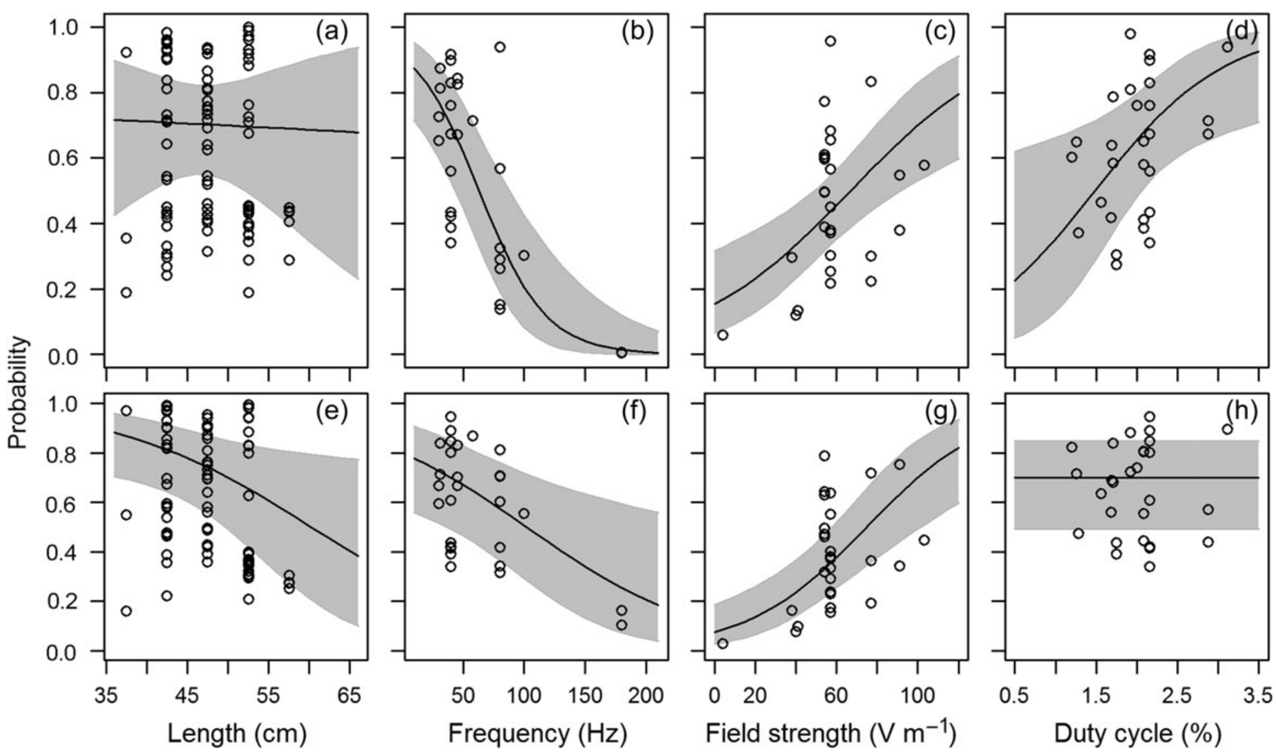

Figure 7. The predicted probability of haemorraghes (top panels) and spine fracture (bottom panels) of market-sized cod in relation to body size (cm), pulse frequency (Hz), field strength (V m^{-1}), and duty cycle (%). The grey areas show the 95% confidence range. Probabilities were estimated with the selected GLM models (Table 6) with pulse type 3 (HFK), frequency = 40 Hz, field strength = 100 V m^{-1}, and body size = 50 cm. Open circles show the observed probabilities standardized to the settings of the covariables.

and haemorrhages (Sharber and Carothers, 1988; Sharber *et al.*, 1995). These studies, however, were conducted in freshwater and involved duty cycles >50%. Saltwater studies on Atlantic herring showed vertebral injuries and haemorrhages in 60% of the herring at all combinations of field strength (33–142 V m^{-1}) and exposure (1–12 s) to a 50 Hz sinusoidal AC stimulus (Nordgreen *et al.*, 2008). Injuries occurred mainly in the cranial and caudal regions. A similar observation was reported by Roth *et al.* (2004) for Atlantic salmon and pollock.

The haemorrhages observed in cod are most likely due to an internal bleeding caused by a vertebral fracture as they co-occurred and were located at the same spot, often in the cranial part of the caudal region. In four fish, the haemorrhage was not related to a spine fracture. This could indicate that in rare cases the muscular contraction can be strong enough to rupture small blood vessels in the musculature, as it is unlikely that fractures have gone unnoticed in the thorough inspection of the X-ray pictures.

Effect of body size

The difference in the frequency of fractures observed between small and large cod is in agreement with the notion that large fish will show a stronger response to an electric field because they experience a larger potential difference over their body (Adams *et al.* 1972; Stewart, 1975; Emery 1984; Dalbey and Mcmahon 1996; Dolan and Miranda 2003). This basic property of electrical stimulation explains the species-specific selection characteristics that are related to body shape and specific excitable structures (Mck Bary, 1956; Halsband, 1967). The response of fish to electrical stimuli is believed to be caused by the excitation of the nervous system and muscles (Mck Bary, 1956; Vibert, 1963; Lamarque, 1967). It is suggested that the effect of body size is a function of total surface area (Emery, 1984) or body volume (Dolan and Miranda, 2003), rather than the length of the fish. Lamarque (1990) concluded that any size-related response is probably due to other factors than the direct effect of the electric field to the neural system.

The difference in response with body size may also be due to the ontogenetic change in the morphology of the spine, or due to differences in the mineral content of the vertebrae. Small cod (8–16 cm) have the largest vertebrae in the cranial part of the caudal region, while larger cod (35–76 cm) have the largest vertebrae in the abdominal region of the spine (Fjelldal *et al.*, 2013). In Atlantic salmon, the largest vertebrae have the highest mineral content and are located where the mechanical load imposed during swimming is largest (Fjelldal *et al.*, 2005, 2006). The mineral content of the vertebrae of large cod in our experiments, and hence the mechanical strength, may have been reduced due to decalcification related to the development of the ovaries as suggested by Fjelldal *et al.* (2013) and Soetaert 2015.

The decrease in the probability of fractures with body size as suggested by our experiments with large cod contrasts with the basic property discussed above. This result may be specific for the heterogeneous electric fields generated by pulse trawls. Small cod were exposed to a high field strength over their whole body. Large cod received a high field strength only in the head and trunk regions (V1–V19), while the injuries mainly occurred in the tail region (V15–V25) that was exposed to a lower field strength. Further research is needed to the effect of heterogeneous fields on the effect of body size on the probability and type of injuries.

Experimental pulse settings affecting injuries

Field strength: The observed increase in the probability of injuries with field strength is in line with the increase in the muscular contraction with field strength (McMichael, 1993; Spencer, 1967). A field strength of 37 V m^{-1} seems to be a threshold level below which injuries are rare. Nordgreen *et al.* (2008) found that injuries in Atlantic herring were reduced <33 V m^{-1} at 1 s duration, but increased when the exposure duration increased. For the same voltage over the electrodes, the field strength generated in our experiments will be higher than *in situ* because of the deflection of the electrical field by the isolated bottom of the tank. In addition, the distance between the electrodes in the experiments was 10 cm (23%) shorter than in the current fisheries.

Duty cycle: Our study shows that injuries already occurred with duty cycles of 1.2—3.1%, much lower than the duty cycles of 50–100% used in the studies with Atlantic herring, salmon, and pollock (Roth *et al.*, 2004; Nordgreen *et al.*, 2008). This suggests that the energy content of the pulse may be less decisive for causing injuries.

Pulse frequency: Injuries in large cod decreased with increasing frequency and were zero at 180 Hz. A similar effect was found by Roth *et al.* (2004) in Atlantic salmon, rainbow trout, and pollock exposed to a sinusoidal AC using frequencies between 500 and 1000 Hz. The effect was less consistent for pollock when exposed to a square wave AC.

Pulse shape and other attributes: The Delmeco-1 pulse has an exponential leading slope that resulted in a slightly higher injury probability than the steeper square wave shape of HFK. Roth *et al.* (2004) compared injuries in pollock and Atlantic salmon that were exposed to sinusoidal AC and square wave AC and did not find a significant difference between species. Injuries in pollock, however, were less dependent on the pulse frequency and duration when exposed to square wave AC (Roth *et al.*, 2004). This supports the suggestion that pulse shape affects the injury probability (Sharber *et al.* 1995; Sharber and Carothers, 1988; Roth *et al.* 2004). Our results, that electrical pulses with a low-energy content (2% duty cycle) can trigger muscular contractions and cause spinal fractures, suggest the importance of the pulse shape. In our experiments, we did not distinguish between the pulse edge and the bipolar interval.

Impacts on the survival

Vertebral fractures will likely reduce the survival of the fish. A fracture at the basis of the neural arch may damage the nervous system and may result in paralysis. A fracture at the basis of the haemal canal may rupture the aorta and the vena caudalis and may cause an internal bleeding and a reduction of the capacity of the circulatory system. The vertebral column of teleost fish is specialized to an aquatic mode of life and a fracture of vertebrae, or a rupture of the intervertebral ligaments, will hamper swimming. In addition, indirect effects may occur related to repair processes and the immune system. Wild rainbow trout observed over a period of 355 days showed that fish with moderate-to-severe injury (vertebral misalignment and fracture) had lower growth and a lower physical condition than fish with no or little vertebral injury (Dalbey and McMahon, 1996). Reduced swimming performance may also increase the susceptibility to predation.

The field strength that a cod will experience when entering a pulse trawl, and hence the probability to develop an injury, depends on its position relative to the electrodes (Figure 8). The effect of the electrical stimuli on a fish, that is located just outside the pulse trawl, will be negligible. The inference that the probability of developing a spine fracture is low in a substantial part of the mouth of the trawl

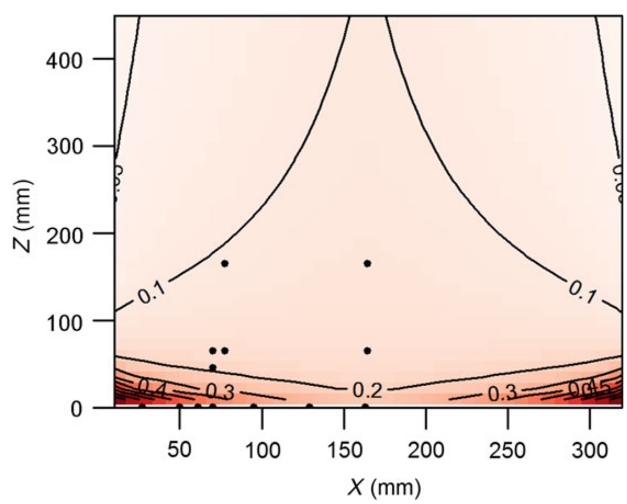

Figure 8. Probability of a spine fracture in a 50 cm market-sized cod in the vertical plane between a pair of conductors. The conductors are positioned at $X = 0$ and $X = 325$ mm with the headrope level at $Z = 430$ mm. The probabilities were estimated with the peak field strength values shown in Figure 3b.

is consistent with the reported injury probabilities in commercial catches. In a sample of 25 cod caught in 2007, 8% individuals had vertebral injuries (van Marlen, *et al*., 2007). A study in 2010 reported fractures of the spine in 9% of the 45 cod investigated (van Marlen *et al*., 2014).

The injuries inflicted by electrical stimulation in pulse trawl are not expected to adversely impact the population dynamics of cod. Although market-sized cod may suffer from pulse-related injuries, these fish will be landed anyhow. The cod, that are small enough to escape through the 80 mm meshes of commercial pulse trawls (50% retention length is around 18 cm, Reeves *et al*., 1992), did not develop injuries and resumed normal behaviour after exposure. It is unknown whether electrical stimulation will affect their susceptibility to predation during the recovery phase after electrical stimulation. Cod in the discard size range (17–35 cm), although not tested in our experiments, may develop vertebral injuries as spine fractures were observed in cod of 20, 23, 27, and 55 cm (van Marlen *et al*., 2014). Because the survival rate of cod discards in bottom trawl fisheries is low (Lindeboom and de Groot, 1998; Depestele *et al*., 2014), we do not expect that pulse trawling lead to additional mortality in discarded cod.

Measures to mitigate injuries

Although the injuries inflicted by the pulse trawl is restricted to market-sized cod and will not increase the mortality of the population, there is an economic and an ethical reason to reduce the injuries: (i) injured cod may fetch a lower price; (ii) reduction in the discomfort (animal welfare).

Our experiments showed that the probability of injuries may be reduced by increasing the pulse frequency. Because the field strength is inversely proportional to the diameter of the conductor, an increase in diameter can be used to reduce the field strength to a level where injuries are reduced http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elecyl.html, while still invoking a cramp response in the target species.

The decline in the probability of injuries in the vertical plane suggests that when cod can be deterred upwards to a level of ≥100 mm above the seabed injuries would reduce. A reduction of the bycatch of cod in the flatfish fishery is also desirable from a fisheries management perspective, as the cod population in the North Sea is in a poor state and needs special protection (Batsleer *et al*, 2013; Kraak *et al*., 2013).

In this study, we only looked at the injuries in cod. Whether pulse trawling may incur injuries in other species remains to be investigated. Van Marlen *et al.* (2014) reported a spine injury in 1 of 47 whiting caught in a pulse trawl. Soetaert (2015) was unable to inflict injuries in sole and sea bass exposed to electrical pulses including pulse settings used in commercial fisheries. Further research to the biomechanical aspects of muscle contractions in relation to the morphology and strength of the bones in different parts of the body, as well as in different fish species, is required to elucidate the mechanistic basis for understanding the observed pattern in injuries (Soetaert, 2015).

Ethical considerations

The exposure experiments reported in this paper will undoubtedly have caused discomfort. Whether the discomfort is acceptable will depend on the knowledge obtained. The effects were studied over a range of pulse parameters, including the settings of the gear currently in use, and provided information about possibilities for mitigation. The discomfort of the experimental fish should be compared with the possible advantages of the novel pulse trawl method which may result in a reduction in the bycatch of undersized fish of target and non-target species, and a reduction of the adverse effects on the benthic ecosystem (van Marlen *et al*., 2014; Batsleer *et al*., 2016; Depestele *et al*., 2016). Although there is no agreed approach to deal with animal welfare aspects of commercial fisheries (Diggles *et al*., 2011), traditional beam trawling may have a poor performance. It is known to inflict damage to the fish and benthic invertebrates in the path of the trawl due to the combined effects of tickler chains, large amount of hard debris retained (benthic invertebrates, stones, sand, and waste) and high towing speed (6–7 knots) (Lindeboom and de Groot, 1998). As a consequence, only few fish survive the catching process when released (van Beek *et al*., 1990; Depestele *et al*., 2014). Pulse trawling is characterized by a lower catch volume and a reduced amount of debris and will likely reduce the damage inflicted on the animals caught. Survival experiments of sole and plaice discards suggest that the survival chance in the pulse fishery is higher than in the traditional beam trawl fishery (van Marlen, pers. comm.). Further research is needed to compare the effects of both fishing methods on the welfare of the fish and benthic invertebrates.

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References

Adams, W. J., Behmer, D. J., and Weingarten, W. O. 1972. Recovery of shocked common shiner, *Notropis cornutus*, related to electric energy. Transactions of the American Fisheries Society, 101: 553–555.

Batsleer, J., Hamon, K., van Overzee, H. M. J., Rijnsdorp, A. D., and Poos, J. J. 2016. Mixed fisheries management: Is the ban on discarding likely to promote more selective and fuel efficient fishing in the Dutch flatfish fishery? Fisheries Research, 174: 118–128.

Batsleer, J., Poos, J. J., Marchal, P., Vermard, Y., and Rijnsdorp, A. D. 2013. Mixed fisheries management: protecting the weakest link. Marine Ecology Progress Series, 479: 177–190.

Daan, N. 1997. TAC management in North Sea flatfish fisheries. Journal of Sea Research, 37: 321–341.

Dalbey, S. R., and McMahon, T. E. 1996. Effect of electrofishing pulse shape and electrofishing-induced vertebral injury on long-term growth and survival of wild rainbow trout. North American Journal of Fisheries Management, 16: 560–569.

de Groot, S. J. 1984. The impact of bottom trawling on the benthos fauna of the North Sea. Ocean Management, 9: 177–190.

de Groot, S. J., and Boonstra, G. P. 1970. Preliminary notes on the development of an electrical tickler chain for sole (Solea solea L.). ICES C.M., 1970/B: 4.

de Haan, D., van Marlen, B., Kristiansen, T. S., and Fosseidengen, J. E. 2008. The effect of pulse stimulation on biota—Research in relation to ICES advice—Progress report on the effects on cod. Imares Report Number C098/08.

Depestele, J., Desender, M., Benoît, H. P., Polet, H., and Vincx, M. 2014. Short-term survival of discarded target fish and non-target invertebrate species in the "eurocutter" beam trawl fishery of the southern North Sea. Fisheries Research, 154: 82–92.

Depestele, J., Ivanović, A., Degrendele, K., Esmaeili, M., Polet, H., Roche, M., Summerbell, K., *et al.* 2016. Measuring and assessing the physical impact of beam trawling. ICES Journal of Marine Science, doi 10.1093/icesjms/fsv056.

Diggles, B., Cooke, S., Rose, J., and Sawynok, W. 2011. Ecology and welfare of aquatic animals in wild capture fisheries. Reviews in Fish Biology and Fisheries, 21: 739–765.

Dolan, C. R., and Miranda, L. E. 2003. Immobilization thresholds of electrofishing relative to fish size. Transactions of American Fisheries Society, 132: 969–976.

Emery, L. 1984. The Physiological Effects of Electrofishing: Cal-NEA Wildlife Transactions, 1984. pp. 59–72.

EU. 1998. Council Regulation (EC) No. 850/98 of 30 March 1998 for the conservation of fishery resources through technical measures for the protection of juveniles of marine organisms. Article 31: non-conventional fishery techniques (OJL 125, 27.4.1998). 55 pp.

Fjelldal, P. G., Lock, E. J., Grotmol, S., Totland, G. K., Nordgarden, U., Flik, G., and Hansen, T. 2006. Impact of smolt production strategy on vertebral growth and mineralisation during smoltification and the early seawater phase in Atlantic salmon (*Salmo salar*, L.). Aquaculture, 261: 715–728.

Fjelldal, P. G., Nordgarden, U., Berg, A., Grotmol, S., Totland, G. K., Wargelius, A., and Hansen, T. 2005. Vertebrae of the trunk and tail display different growth rates in response to photoperiod in Atlantic salmon, *Salmo salar* L., post-smolts. Aquaculture, 250: 516–524.

Fjelldal, P. G., Totland, G. K., Hansen, T., Kryvi, H., Wang, X., Søndergaard, J. L., and Grotmol, S. 2013. Regional changes in vertebra morphology during ontogeny reflect the life history of Atlantic cod (*Gadus morhua* L.). Journal Anatomy, 222: 615–624.

Fjelldal, P. G., van der Meeren, T., Jørstad, K. E., and Hansen, T. J. 2009. A radiological study on vertebral deformities in cultured and wild Atlantic cod (*Gadus morhua*, L.). Aquaculture, 289: 6–12.

Fredenberg, W. A. 1992. Evaluation of electrofishing-induced spinal injuries resulting from field electrofishing surveys in Montana. Montana Department of Fish, Wildlife, and Parks, Helena, MT [abstract reprinted (1992). *In* Western Division American Fisheries Society, July 13–16, 1992, Program Abstracts [annual meeting, Fort Collins, Colorado], p. 13. Ed. by Anonymous. American Fisheries Society Western Division, Bethesda, MD.

Halsband, E. 1967. Basic principles of electric fishing. *In* Fishing with Electricity, Its Application to Biology and Management, pp. 57–64. Ed. by R. Vibert Fishing News (Books) Ltd., London.

Holmes, R., McBride, D. N., Viavant, T., and Reynolds, J. B. 1990. Electrofishing induced mortality and injury to rainbow trout, Arctic grayling, humpback whitefish, least cisco, and northern pike. Fishery Manuscript 90-3, Alaska Department of Fish and Game Division of Sport Fish, Anchorage, AK. 95 pp.

Horak, D. L., and Klein, W. D. 1967. Influence of capture methods on fishing success, stamina, and mortality of rainbow trout (*Salmo gairdneri*) in Colorado. Transactions of the American Fisheries Society, 96: 220–222.

ICES. 2010. Report of the Workshop to Assess the Ecosystem Effects of Electric Pulse Trawls (WKPULSE) – 24–26 February 2010, IJmuiden, The Netherlands.

ICES. 2011. Report of the Study Group on Electrical Trawling (SGELECTRA). ICES CM 2011/SSGESST:09. 93 pp.

Jennings, S., and Kaiser, M. J. 1998. The effects of fishing on marine ecosystems. Advances in Marine Biology, 34: 201–352.

Kraak, S. B. M., Bailey, N., Cardinale, M., and Darby, C. 2013. Lessons for fisheries management from the EU cod recovery plan. Marine Policy, 37: 200 − 213.

Lamarque, P. 1967. Electrophysiology of fish subject to the action of an electric field. *In* Fishing with Electricity, Its Application to Biology and Management, pp. 65–92. Ed. by R. Vibert. Fishing News (Books) Ltd, London.

Lamarque, P. 1990. Electrophysiology of fish in electric fields. *In* Fishing with Electricity, Applications in Freshwater Fisheries Management, pp. 4–33. Ed. by I. G. Cowx, and P. Lamarque. Fishing News Books, Blackwell Scientific Publications. Oxford, UK.

Lindeboom, H. J., and de Groot, S. J. 1998. The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems. NIOZ Report 1998-1/RIVO Report C003/98. Netherlands Institute for Sea Research, Den Burg, Texel, The Netherlands.

Mck Bary, B. 1956. The Effect of Electric Fields on Marine Fishes. Marine Research, No. 1. p. 32. Scottish Home Department. Edinburgh, Her Majesty's Stationary Office, Edinburgh.

McMichael, G. A. 1993. Examination of electrofishing injury and short-term mortality in hatchery rainbow trout. North American Journal of Fisheries Management, 13: 229–233.

Murray, F., Copland, P., Boulcott, P., Robertson, M., and Bailey, N. 2016. Impacts of electrofishing for razor clams (Ensis spp.) on benthic fauna. Fisheries Research, 174: 40–46.

Nordgreen, A. H., Slinde, E., Møller, D., and Roth, B. 2008. Effect of various electric field strengths and current durations on stunning and spinal injuries of Atlantic Herring. Journal of Aquatic Animal Health, 20: 110–115.

Opstad, I., Fjelldal, P. G., Karlsen, Ø., Thorsen, A., Hansen, T. J., and Taranger, G. L. 2013. The effect of triploidization of Atlantic cod (*Gadus morhua* L.) on survival, growth and deformities during early life stages. Aquaculture, 388: 54–59.

Polet, H., Delanghe, F., and Verschoore, R. 2005a. On electrical fishing for brown shrimp (*Crangon crangon*)—I Laboratory experiments. Fisheries Research, 72: 1–12.

Polet, H., Delanghe, F., and Verschoore, R. 2005b. On electrical fishing for brown shrimp (*Crangon crangon*)—II Sea trials. Fisheries Research, 72: 13–27.

Poos, J. J., Turenhout, M. N. J., van Oostenbrugge, H. A. E., and Rijnsdorp, A. D. 2013. Adaptive response of beam trawl fishers to rising fuel cost. ICES Journal of Marine Science, 70: 675–684.

R Core Team. 2013. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Reeves, S. A., Armstrong, D. W., Fryer, R. J., and Coull, K. A. 1992. The effects of mesh size, cod-end extension length and cod-end diameter on the selectivity of Scottish trawls and seines. ICES Journal of Marine Science, 49: 279–288.

Rijnsdorp, A. D., Poos, J. J., Quirijns, F. J., HilleRisLambers, R., de Wilde, J. W., and den Heijer, W. M. 2008. The arms race between fishers. Journal of Sea Research, 60: 126–138.

Roth, B., Møller, D., and Slinde, E. 2004. Ability of electric field strength, frequency, and current duration to stun farmed Atlantic salmon and pollock and relations to observed injuries using sinusoidal and square wave alternating current. North American Journal of Aquaculture, 66: 208–216.

Sharber, N. G., and Black, J. S. 1999. Epilepsy as a unifying principle in electrofishing theory: a proposal. Transactions of the American Fisheries Society, 128: 666–671.

Sharber, N. G., and Carothers, S. W. 1988. Influence of electrofishing pulse shape on vertebral injuries in adult rainbow trout. North American Journal of Fisheries Management, 8: 117–122.

Sharber, N. G., Carothers, S. W., Sharber, J. P., de Vos, J. C., and House, D. A. 1995. Reducing electrofishing-induced injury of rainbow trout: response to comment. North American Journal of Fisheries Management, 15: 965–968.

Soetaert, M. 2015. Electrofishing: exploring the safety range of electric pulses for marine species and its potential for further innovation. PhD thesis, University Gent, Belgium. 243 pp.

Soetaert, M., Chiers, K., Duchateau, L., Polet, H., Verschueren, B., and Decostere, A. 2015b. Determining the safety range of electrical pulses for two benthic invertebrates: brown shrimp (*Crangon crangon* L.) and ragworm (*Alitta virens* S.). ICES Journal of Marine Science, 72: 973–980.

Soetaert, M., Decostere, A., Polet, H., Verschueren, B., and Chiers, K. 2015a. Electrotrawling: a promising alternative fishing technique warranting further exploration. Fish and Fisheries, 16: 104–124.

Spencer, S. L. 1967. Internal injuries of largemouth bass and bluegills caused by electricity. Progressive Fish-Culturist, 29: 168–169.

Stewart, P. A. M. 1975. Catch selectivity by electrical fishing systems. Journal du Conseil International Pour L'Exploration de la Mer, 36: 106–109.

Stewart, P. A. M. 1977. A study on the response of flatfish (Pleuronectidea) to electrical stimulation. Journal du Conseil International Pour L'Exploration de la Mer, 37: 123–129.

Taal, C., Bartelings, H., Beukers, R., Klok, A. J., and Strietman, W. J. 2010. Visserij in cijfers 2010. LEI-rapport 2010-057. 130 pp.

van Beek, F. A. 1998. Discarding in the Dutch beam trawl fishery. ICES CM 1998/BB:5.

van Beek, F. A., van Leeuwen, P. I., and Rijnsdorp, A. D. 1990. On the survival of plaice and sole discards in the otter-trawl and beam-trawl fisheries in the North-Sea. Netherlands Journal of Sea Research, 26: 151–160.

van Marlen, B., van de Vis, H., de Haan, D., Burggraaf, D., van der Heul, J., and Terlouw, A. 2007. The effect of pulse stimulation on biota—Research in relation to ICES advice—Progress report with preliminary results. IMARES-Report Nr. C098/07. 24 pp.

van Marlen, B., Wiegerinck, J. A. M., van Os-Koomen, E., and van Barneveld, E. 2014. Catch comparison of pulse trawls and a tickler chain beam trawl. Fisheries Research, 151: 57–69.

van Stralen, M. R. 2005. De Pulskor. MarinX-rapport 2005.26. 26 pp.

Vibert, R. 1963. Neurophysiology of electric fishing. Transactions of the American Fisheries Society, 92: 265–275.

Handling editor: Howard Browman