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Quo Vadimus

Guidelines for defining the use of electricity in marine electrotrawling

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Electricity can be used to facilitate fish and invertebrate capture in both marine and freshwater environments. In freshwaters, electrofishing is largely used for research or management purposes. In marine environments electrofishing is principally used in the form of electrotrawling for the commercial capture of fishes and benthic invertebrates, in particular common sole (*Solea solea* L.), brown shrimp (*Crangon crangon* L.), and razor clams (*Ensis* spp.). The terminology and definitions used to describe the electrical stimulus characteristics and experimental set-ups have, so far, been diverse and incomplete, hampering constructive discussion and comparison of electrofishing studies. This paper aims to (i) harmonize existing terminology, abbreviations, and symbols, (ii) offer best practice recommendations for publishing results, and (iii) provide a concise and comprehensible reference work for people unfamiliar with this topic. By incorporating common practice in marine electric pulse trawling terminology and related freshwater electrofishing studies, based on existing terms where possible, we provide a framework for future studies. The suggested guideline is recommended by the ICES Working Group on Electrical Trawling as a constructive approach to improved communication standards in electrofishing and electrical pulse stimulation research and publications.

Keywords: electrical pulse parameters, electrofishing, guidelines, ICES, pulse trawling, terminology, WGELECTRA

Introduction

The history of freshwater electrofishing goes back to the 19th century, but it was not until the second part of the 20th century that it became an important scientific fish sampling technique for population and community surveys in freshwater systems (Vibert, 1967b; Snyder, 2003; Soetaert *et al.*, 2015; Beaumont, 2016). The technique uses an electric field applied between two electrodes to induce galvanotaxis and temporary immobility, or narcosis, of the fish (Taylor *et al.*, 1957; Snyder, 2003). This allows easy and accessible collection of fish near the electrodes with a dip net (Sharber and Black, 1999; Beaumont *et al.*, 2002; Snyder, 2003).

This freshwater electrofishing knowledge was adopted in a quest to increase the catch efficiency and/or reduce fuel costs of bottom trawls by means of electrical stimulation in so-called "electrotrawls" (e.g. Pease and Seidel, 1967; vanden Broucke, 1973; Boonstra and de Groot, 1974; Stewart, 1974; Horn, 1976, Watson, 1976; Namboodirj *et al.*, 1977; Stewart, 1977; Agricola, 1985). Despite promising results in both the North Sea common sole (*Solea solea* L.) and brown shrimp (*Crangon crangon* L.) fisheries, international criticism, fuelled by fear of further increasing catch efficiency of the beam trawling fleet, resulted in a ban by the German government in 1987, the Dutch Ministry of Agriculture and Fisheries in 1988 and later in 1998 by the

Council of the European Union (van Marlen, 1997; Council of the European Union, 1998; Linnane *et al.*, 2000). However, in following years around 3000 vessels in China used electrical pulses to target (mainly penaeid) shrimp (Yu *et al.*, 2007). Yet, lack of regulation and misuse of the electrical parameters resulted in a collapse of commercial shrimp stocks and a ban of this fishing method in 2001 (Yu *et al.*, 2007). After almost two decades, renewed interest led to a partial lift of the ban in the European Union by means of derogations, allowing experimental use and development of electrotrawls from 2006 onwards (Council of the European Union, 2005, 2006; Government of the Netherlands, 2014; ICES, 2018). In the following years, ~85 beam trawlers have switched to pulse trawling in the southern North Sea and reduced or replaced their conventional mechanical stimulators such as bobbins or tickler chains for electrodes generating pulsed electric fields (Haasnoot *et al.*, 2016; Sutherland *et al.*, 2016; ICES, 2018).

At present, three different types of marine electrotrawls are known to be used commercially in Europe targeting three different species: common sole, brown shrimp, and razor clams (*Ensis* spp.) (e.g. Soetaert *et al.*, 2015; Murray *et al.*, 2016). The first two types are alternatives for conventional beam trawls targeting flatfish and shrimp and are commonly called "pulse trawls" since they use pulses of electricity (i.e. a variable duration of energization interspersed with periods of no energization). A 1–2 s exposure of the animals to the electric field between the electrodes towed over the seabed enables fishermen to target brown shrimp and common sole (Soetaert *et al.*, 2015). The use of this technique results in reduced fuel consumption, bottom impact, and by-catch rates (Taal and Hoefnagel, 2010; van Marlen *et al.*, 2014; Depestele *et al.*, 2016, 2019; Tiano *et al.*, 2019; Verschueren *et al.*, 2019). Primarily only two reactions to the electrical pulse stimulations are used to aid capture, i.e. a startle pulse for brown shrimp using a frequency (f) of five cycles per second [hertz, Hz] and a cramp pulse for common sole using around 40 Hz. However, continuous innovations by different manufacturers and changes in electrode configurations by fishermen have led to differences in pulse parameter settings used in the field (ICES, 2018). Latterly, a third type of electrotrawl exists targeting razor clams and is used in Scotland (Breen *et al.*, 2011; Woolmer *et al.*, 2011; Murray *et al.*, 2014, 2016). In contrast to the ~1 s electrical pulse stimulus used for common sole and brown shrimp, razor clams are exposed to 1 min of continuous alternating current (AC) to drive clams from their burrows where they are collected by divers or, less commonly, by dredges towed behind the electrodes. Due to the wide and increasing number of species exposed to electrical stimulation, in this document, unless a specific species is stated, the term "fish" can apply to other organisms that are being caught or affected by the electrofishing apparatus.

One of the reasons marine electrotrawling for common sole is still controversial (Stokstad, 2018), is the spinal injuries and flesh damage observed in Atlantic cod (*Gadus morhua* L.) which are by-catch in electrotrawls targeting common sole (van Marlen *et al.*, 2014; de Haan *et al.*, 2016; Soetaert *et al.*, 2016c). This drawback is also well documented in freshwater research, especially in Salmonidae, but has been reduced by optimizing the waveforms pulse settings used (Snyder, 2003). Current European regulations ban the use of AC waveforms and advise on <60 Hz pulsed direct current (PDC) where used in freshwater electrofishing (Anon., 2003). However, these settings are used by at least one marine equipment manufacturer of pulse trawls targeting common sole, which may explain why injuries in by-catch of Atlantic cod are encountered in this fishery and not in pulse trawls targeting brown shrimp using a 5 Hz square-wave PDC startle pulse (Desender *et al.*, 2016; Soetaert *et al.*, 2016a). Hence marine electrotrawling targeting common sole may be optimized further by learning from electrofishing methods used to capture fish in freshwater environments. However, an ethical assessment of pulse trawling and/or optimization of the pulse settings will be a trade-off between minimal electrically induced harm on by-catch species such as Atlantic cod, optimal catch efficiency for the target species common sole, and other (in)direct effects on other caught species resulting from different gear riggings or fishing behaviour, e.g. by fishing at slower sailing speeds or choosing other fishing grounds. Indeed, the exposure to a single electrical stimulus of ~1 s represents only a fraction of the entire catch process (~120 min excl. on-deck processing), during which the captured fish are continuously being sandblasted and impacted by by-catch stones and hard-bodied invertebrates. Since pulse trawls targeting flatfish move much slower and show a large reduction in by-catch of stones and benthic invertebrates (van Marlen *et al.*, 2014), the overall impact on fish may well be smaller than conventional beam trawls. This is illustrated by undersized European plaice (*Pleuronectes platessa* L.), common sole, and dab (*Limanda limanda* L.) caught by pulse trawlers having a higher survival probability and vitality index compared to fish caught by conventional beam trawls (van der Reijden *et al.*, 2017) and by the higher price pulse trawl fishermen receive for their fish.

With the benefits that could be gained from electrotrawling it is important that structured research continues. Critical to this is a clear and thorough description of the characteristics of any electrical parameters being tested or used. Unfortunately, no consistent approach exists for the description of electrical (pulse) parameters used in marine electrotrawling laboratory and field research, creating unnecessary confusion, especially when abbreviations may have different meanings. For example, the same waveform was labelled as both "a 40 Hz bipolar pulse" and "80 Hz pulsed bipolar current" (PBC) in studies with Atlantic cod (de Haan *et al.*, 2016; Soetaert *et al.*, 2016a, b, c). Furthermore, inadequate descriptions of experimental designs (e.g. tank size, and distance and orientation of the animal with respect to the electrodes) and environmental conditions (e.g. water conductivity), can make it impossible to compare studies and reveal possible causes for deviating findings. Finally, an unambiguous description is needed to properly document and monitor the settings used on vessels and to allow for control and enforcement of those regulations by local authorities.

This paper provides information on the physiological effects on organisms and physical parameters of electrical (pulse) stimulation. The paper also includes an explanation of basic principles using standard nomenclature, symbols, and units. In addition, we propose a set of definitions and abbreviations, enabling usage of harmonized terminology and descriptions of electrical (pulse) parameters in scientific publications as well as in management and enforcement documents.

Physiological responses of organisms exposed to electrical stimulation

External electrical stimulation can affect both the nervous system and muscles and is widely used in medical applications (e.g. Zoll, 1952; Basser and Roth, 2000; Peckham and Knutson, 2005). Neurons and muscle fibres use electrical signals for information transfer (e.g. Hodgkin, 1951; Hodgkin and Huxley, 1952). Neurons integrate synaptic potentials and may transmit information to other neurons or to muscle fibres via action potentials (e.g. Bullock, 1951; Fetcho, 1991). In muscle fibres, the synaptic potentials generated at the neuromuscular junction may lead to muscle contraction (e.g. Hodes, 1953; Fatt, 1954). A single action potential causes a brief and weak twitch of a muscle fibre (e.g. Hodes, 1953; Hunt and Kuffler, 1954). Larger muscle forces are produced by recruiting multiple fibres, and by increasing the frequency of action potentials, leading to temporal summation of contractive force (e.g. Hunt and Kuffler, 1954).

In fish, patterns of contraction required for swimming are coordinated by interneurons in the spinal cord, generating rhythmic, and alternating contractions on the left-and-right side of the body (e.g. Uematsu, 2008; McLean and Fetcho, 2009; Fetcho and McLean, 2010). External electrical stimulation by electrofishing interferes with normal functioning by inducing action potentials in neurons and/or muscle fibres. This simultaneously stimulates both sides of the fish, leading to uncontrolled behaviour, in which mutual left–right inhibition no longer works. In freshwater electrofishing direct current (DC) or pulsed DC waveforms (PDC) are used. This leads at the positive electrode (anode) to four different responses of increasing intensity as fish are exposed to stronger electric field strengths as they get closer to the anode: fright, electrotaxis, electronarcosis, and tetanus. At the negative electrode (cathode), fright and aversion behaviours are exhibited. At increasingly intense stimulation, detrimental effects include cardiac or respiratory failure, injury, stress, and mortality; with mortality effects being both immediate or delayed. However, the specific response of an animal depends on many factors, such as species, body shape and volume, and pulse stimulation parameters, making it complex to provide a complete and conclusive overview, for both electrofishing in freshwater and marine environments. For review, see Vibert (1967a), Sternin *et al.* (1976), Beaumont *et al.* (2002), Snyder (2003), Polet (2010), and Beaumont (2016).

Marine electrotrawls generate electric fields of continuously changing polarity between two moving identical electrode arrays. As consequence, there is no electrotaxis or -narcosis but other responses are aimed for depending on the targeted species. In electrotrawling for razor clams, the electrical settings elicit a voluntary escape response of the target species during which they emerge from the sediment; responses of non-target species vary and are species-specific (Breen *et al.*, 2011; Woolmer *et al.*, 2011; Murray *et al.*, 2014, 2016). In electrotrawling targeting shrimp, the ~1 s electrical pulse stimulus induces a startle response consisting of escape jump swimming behaviour which disperses shrimp from the sediment into the water column and makes other animals, such as fishes, twitch while still allowing them to swim voluntarily (e.g. Polet *et al.*, 2005a, b; Soetaert *et al.*, 2014, 2016d; Desender *et al.*, 2016). In electric pulse trawling targeting common sole, the ~1 s electrical pulse parameters are aimed at invoking a muscle cramp response. The muscle cramp disables the fish' escape response of burrowing deeper in the sediment and makes them bend in a U-shape, after which they are scooped up by the ground rope of the fishing gear (Soetaert *et al.*, 2015). This muscle cramp is known in both freshwater electrofishing and marine electrotrawling to potentially cause internal injuries such as fractures and dislocations of the vertebral column, which may be accompanied by haemorrhages (Snyder, 2003; van Marlen *et al.*, 2014; de Haan *et al.*, 2016; Soetaert *et al.*, 2016a, b, c). These side effects result from simultaneous electrically induced muscle contractions at both sides of the fish' body, an unnatural response because mutual inhibition via interneurons in the spinal cord normally prevents simultaneous contractions of left-and-right swimming muscles in fish (e.g. Uematsu, 2008; Fetcho and McLean, 2010) and mainly occurs in fusiform fish with a high number of small vertebrae such as trout and salmon species (Snyder, 2003) or Atlantic cod (Soetaert *et al.*, 2018).

Electric principles of electrofishing

An electric field is generated in the water by a power supply that provides power to electrodes in which the charge flows between the negatively charged electrode(s), i.e. cathode(s), and the positively charged electrode(s), i.e. anode(s) (Snyder, 2003; Beaumont, 2016). In the context of electrofishing, "electrodes" are the conductive parts of the electric circuit in contact with the water. The electrodes may be mounted on, or separated by, non-conducting elements (insulators) which together can be termed the electrode array (Figure 1). These descriptions will be applied throughout the manuscript and are strongly advised to be adopted in future research.

When a circuit with electrodes placed in water is charged, a potential difference (V, [volt, V]) is generated between the electrodes. Charged ions will flow between the anode and cathode and induce an electrical current (I, [ampere, A]) in the water between the electrodes. The amount of current between the electrodes at a given potential difference is related to the electrical resistance (R, [ohm, Ω]) of the circuit according to Ohm's law ($V = I \times R$). Electrical resistance measures the difficulty an electric force encounters when passing a current through a circuit. Resistivity measures how strongly a given substance opposes an electric current (ρ, [ohm − metre, Ω m]). When measuring the ability of a unit of volume of water to conduct electricity it is usual for the reciprocal value of resistance ($1/R$) to be used, this is termed its conductivity (σ, [siemens per metre, S m^{-1}] or [microsiemens per centimetre, µS cm^{-1}]). This conductivity depends on the amount of total dissolved ions in the water (e.g. calcium, sodium) and temperature of the water (UNESCO IES 80). As temperature affects conductivity (and resistivity) the value of conductivity is usually normalized to what it would be at 25 degrees Celsius (specific conductivity) rather than the conductivity at the ambient temperature of the water (ambient conductivity). When describing conductivity it is important to specify which metric is being used and the water temperature. For electrode arrays in water, their resistance comprised several component factors; the resistance of the metal elements of the electrode in air (normally minimal), the geometry of the electrode, the distance apart of the electrodes, and the resistivity/conductivity of the water. This combined electrode array resistance is termed the equivalent resistance of the electrode (R_{eq}). Together with applied voltage it is this metric that determines the power demand of the fishing equipment (Beaumont *et al.*, 2005).

The energy transfer rate of a generator is the power (P, [watt, W]) and can be calculated in three ways: $P = V \times I$,

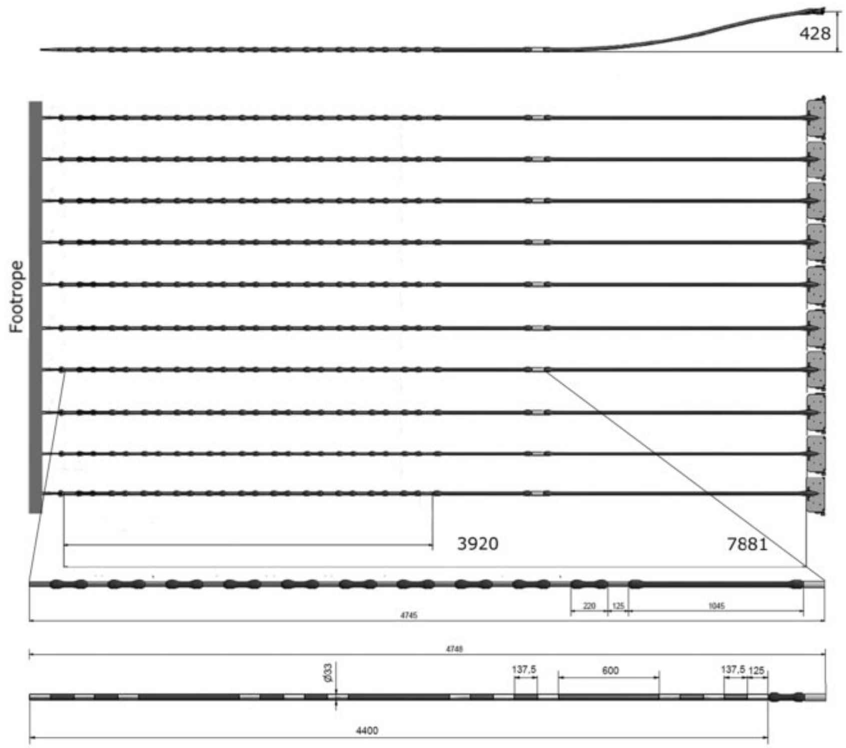

Figure 1. Schematic representation (in mm) of the ten 7.881 m long electrode arrays of a 4 m beam pulse wing used in electrotrawls targeting common sole with a close-up of two possible electrode array types (from HFK Engineering B.V.). The white or grey conductive parts are made of stainless steel or copper respectively and are called electrodes, whereas the longer black parts are non-conductive and called insulators or insulated parts. The entire structure consisting of electrodes and insulators through which the pulse generator releases its electrical current is called an "electrode array." Note that "electrode array," "electrode," and "insulator" were often referred to as "electrode," "conductor," and "isolator" respectively in older electrotrawling manuscripts. It is strongly advised to no longer use the older terminology in future research.

$P = I^2 \times R$, or $P = V^2/R$. However, where AC generators are used for certain electrical equipment (e.g. motors and transformers), time lags between voltage and current (phase shift) in the components leads to more power being needed than the theoretical, or apparent power (S, [volt – ampere, VA]). This disparity is resolved by using a power factor correction (PF) to multiply the apparent power: i.e. $P = S \times PF$. Power Factor (from a source to a load) can vary, depending on the equipment, between 1 and 0, with 1 being no power loss. For example, equipment with a 0.5 *PF* would draw 50% more power than one with a *PF* of 1 and therefore, if the apparent power demand was 1000 VA, it would need 1500 W to run the equipment. This leads to larger power sources being needed. The increase in generator capacity needed due to *PF* is one reason why the use of AC waveforms is attractive to operators. However, the use of capacitors within the power distribution circuit can reduce the power factor. For bankside electrofishing equipment used in freshwater environments a *PF* of 0.6 is commonly used.

The voltage difference between a pair of conductors generates an electric field which is characterized by its strength and orientation. The electric field defines the current flow at each location and can be visualized by electric field lines, indicating the direction of current flow at each location. Alternatively, one can define equipotential lines that run perpendicular to the electric field lines and indicate directions in which there is no net current flow (Figure 2). The potential difference between two sequential equipotential lines is an arbitrary but constant value. Consequently, the distance between subsequent equipotential lines indicates the electric field strength or voltage gradient (E, [volt per metre, V m^{-1}] or [volt per centimetre, V cm^{-1}]). The electric field can also be described by the two-dimensional current density (J) which is the electric current per cross-sectional area of its path [ampere per square centimetre, A cm^{-2}] (Sternin *et al.*, 1976). Current density can be calculated by multiplying the voltage gradient E with the water conductivity (σ). An additional method of describing the amount of power that needs to be transferred into a fish to achieve, for example, immobilization and tetanus, called power density (D, [Watt per cubic centimetre, W cm^{-3}]), was proposed by Kolz and Reynolds (1990). Power density is calculated from J^2/σ. As transferred power density values e.g. immobilization are constant across water conductivities they allow standardization of outputs for different water conductivities (Kolz and Reynolds, 1990; Burkhardt and Gutreuter, 1995; Snyder, 2003; Beaumont, 2016). Although voltage gradient is easier to measure, it is the current and/or power density that is the most significant factor in determining a fish's reaction to an electric field.

If two large and flat "plate shaped" conductors are used, electric field lines will be equally distributed in the water volume and run parallel (i.e. create a homogeneously distributed electric field), whilst equipotential lines are oriented parallel to the conductors' surface (Figure 2a). This set-up's advantage is its

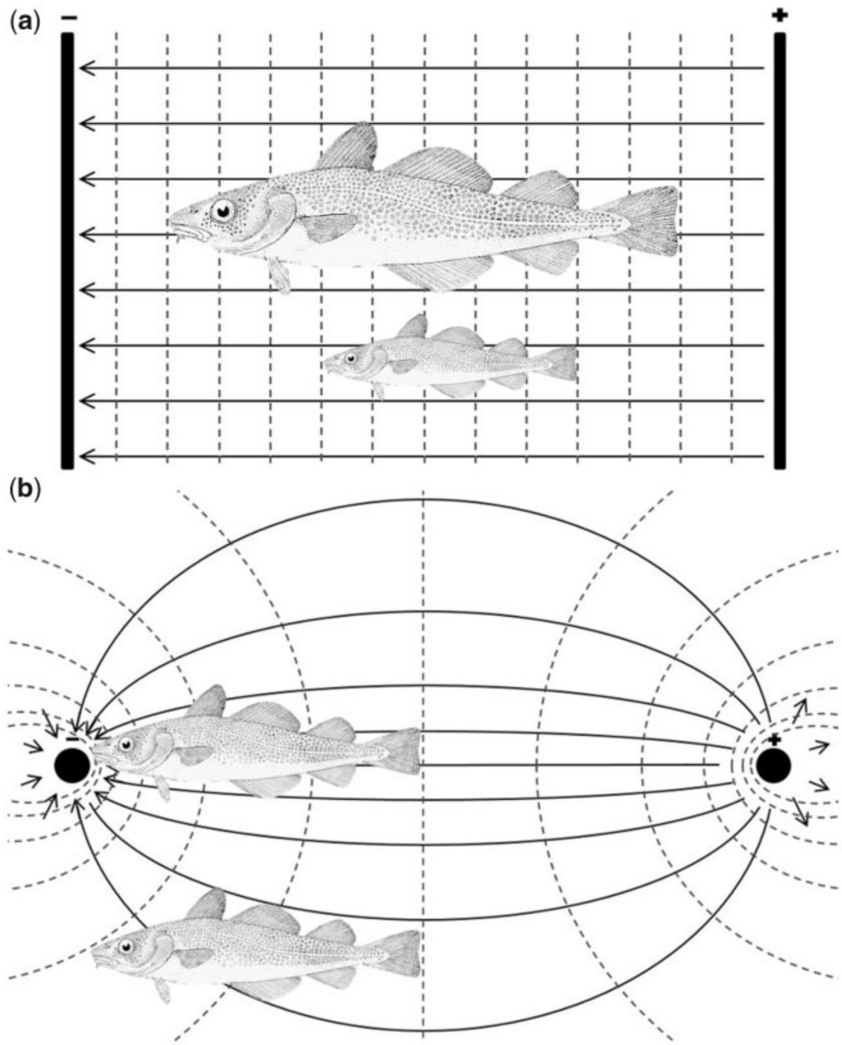

Figure 2. Schematic representation of fish in (a) a homogeneous and (b) heterogeneous electric field (Soetaert *et al.*, 2015). The fish in these hypothetical scenarios have the same conductivity as the surrounding medium and therefore do not affect the electric field. The solid black lines are the electric field lines, representing the current flow between the two conductors (heavy black lines and dots in the top and bottom panel, respectively). The arrows indicate the electric field vectors representing the current flow. The dashed lines are equipotentials representing regions with the same potential. If more equipotential lines cover the fish's body, a larger potential difference, hence a higher current density, is present over its body.

predictability: the electric field strength is constant and uniform and calculated by dividing the applied voltage by the distance between the two conductors. Moreover, the extremities of an animal placed in a homogeneous field will have a constant potential difference, regardless of their position, as long as their orientation remains unchanged. Hence, homogeneous electric fields are used in laboratory set-ups to study the effects of electrical stimulation on organisms, since this design enables standardization with minimum variability in field strengths (Soetaert *et al.*, 2014, 2016a). Note that in a natural environment many factors can distort the idealized model of the electric field propagated from electrodes e.g. by conductive objects being within the field.

In freshwater electrofishing the anodes are usually sphere, ring (torus), or rod shaped electrodes. Cathodes are usually high surface area grids or braided ribbon, which create a low electrical resistance electrode, and thus low field density. In marine electrotrawling, the anode and cathode are always rod shaped and of the same size within an electrode array and fishing gear (Figure 1). This results in a heterogeneously distributed electric field (Figure 2b). Near to the direct surroundings of the electrodes voltage gradient is high, indicating high current density, which decreases with distance from the electrode (Beaumont *et al.*, 2006; de Haan *et al.*, 2016). Hence, the electrode position relative to the fish, can result in a relatively large increase or decrease in the electric field strength experienced (Soetaert *et al.*, 2015; Beaumont, 2016). Therefore, free-swimming fish will experience a wide range of reactions to an electric field depending on their distance to and orientation in the field.

Variables affecting the electric field distribution

Various environmental variables may affect the shape and intensity of the electric field and consequently the effect on exposed animals. Below, we outline the major components that may

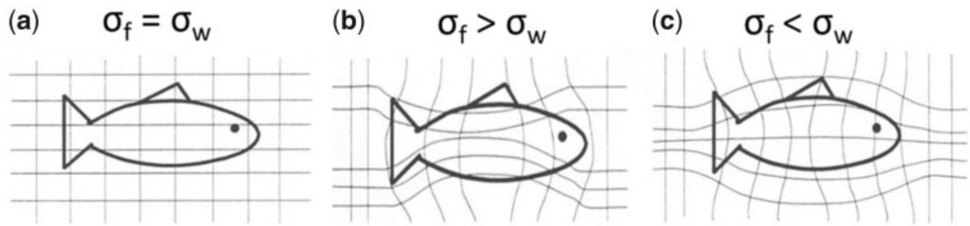

Figure 3. Schematic representation of three idealized distortion patterns of an electric field surrounding a fish with varying relative values of the electrical conductivity of the fish (σ_f) and the ambient conductivity of the water (σ_w) (from Kolz, 2006). The horizontal and vertical lines represent the current lines and the equipotentials, respectively. In a, the conductivity of the fish is the same of the surrounding water (i.e. as used in Figure 2). In b, the fish has a higher conductivity compared to the surrounding water (i.e. relatively low conductive freshwater), which results in lower voltage gradients in the fish compared to the surrounding medium, whereas the voltage gradients in the fish in c (i.e. relatively high conductivity seawater) will be higher compared to the surrounding medium.

constitute these effects on the electric field, i.e. the water, sediment, and electrode array characteristics.

Water

The equivalent resistance of the electrodes determines which electrical settings can be achieved within the limitations of the electrofishing generators being used. As power can be calculated by dividing the voltage squared by resistance (see earlier), higher conductivity water (lower resistivity) will require more power since the equivalent resistance is lower ($P = V^2/R_{eq}$). The conductivity of fish in relation to the surrounding water is important because it determines the amount of electric current transferred from the water to the fish (Whitney and Pierce, 1957; Snyder, 2003). Kolz (1989) also considered that the mismatch between the fish and water conductivity affected the power transferred into the fish and thus the fish's reaction to the electric field. The relationship between the conductivity of the fish and the surrounding medium leads to a concentrating or dissipating effect of the electric field (Figure 3; Sternin *et al.*, 1976) and fish in higher conductivity water will experience a higher current density compared to lower conductivity water (Sternin *et al.*, 1976; Snyder, 2003). This conductivity mismatch results in lower voltage gradients being required to generate sufficient power density to incapacitate the fish in high conductivity water compared to low conductivity water. For example, at very low conductivity water (<20 µS cm^{-1}) voltages of >1000 V are needed to induce narcosis (Beaumont, 2016) compared to 45–65 V used in marine electrotrawling (Soetaert *et al.*, 2015). The presence of other fish nearby also affects the electric field experienced by an individual as, in case of seawater, the electric field will be "concentrated" in a smaller volume of water, hence increasing the electric field strength experienced by an individual fish, as illustrated by D'Agaro and Stravisi (2009). In addition, the variable conductivity of different fish species (Halsband, 1967) may affect reactions, although for simplicity Burkhardt and Gutreuter (1995) used a fixed value for effective fish conductivity of 150 μS cm^{-1} with PDC waveforms (Kolz and Reynolds, 1990).

Sediment

Composition and structure of the sediment may also affect the shape and intensity of the electric field. Factors impacting the electric field distribution in the sediment are particle grain size (i.e. porosity), determining the amount of water present in the sediment, and the amount of organic matter in-between the inorganic particles (Zalewski and Cowx, 1990). Measurements by de Haan and Burggraaf (2018) indicate that electric field strengths are almost evenly distributed in the water volume and the sediment when electrodes are placed on the sediment, although field strengths measured in the sediment were slightly higher than those in the water column at equal distance. Field strengths measurements in the sediment, as well as the variability between replicates, tended to be higher in muddy sediment when compared to the more compact sandy sediment. Consequently, depth of the substrate layer in laboratory experiments, as well as the dimensions and building material of the exposure tank, will affect the electric field distribution around the electrodes. Interactions between the electric field and the sediment, or water surface, are termed boundary effects.

Electrode (array) characteristics

The equivalent resistance of the electrodes is a function of size, shape, surface area, and spacing. High surface area electrodes will have a low resistance and will have a lower probability of injuring fish, because the maximum electric field near the electrodes will be lower compared to electrodes with a smaller surface area (when using the same potential difference and distance). Hence, large electrodes are preferred to minimize injuries (Snyder, 2003; Beaumont *et al.*, 2006).

In marine electrofishing, high water conductivity leads to lower voltage levels being needed to achieve an effective electric field density. Electrode arrays used in marine electrotrawling are either long thin electrodes (1.5 m × ø12 mm) or multiple short electrodes (160–180 mm × ø ~40 mm) alternated by insulators are used on the electrode arrays that are towed over the seafloor (Figure 1). By having electrodes of this design the equivalent resistance of the electrode(s) is increased and thus the power demand reduced. Due to the high power demand of the electrode array in sea water, the pulse shape may be affected if the power supply is not sufficient, e.g. square waveforms having a falling voltage after an initial peak value. It is important to note that when operating multiple electrode arrays using pulsed waveforms in close proximity, pulses are likely to be out of phase and thus create high (potentially damaging) frequencies in the area where the electric fields overlap (Beaumont, 2017).

Movement

Movement of the fish and/or electrode arrays affects the time-duration the fish is exposed to the electrical pulse stimulus. A

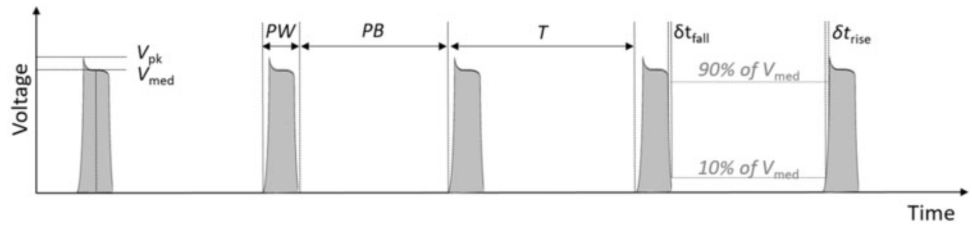

Figure 4. Schematic representation of square wave PDC with overshoot. The indicated waveform parameters are peak voltage (V_{pk}), median voltage (V_{med}), pulse width (PW), pulse interval or break time (PB), period (T), fall time (δt_{fall}), and rise time (δt_{rise}). If the presented time frame is considered on scale with a total duration of 1 s, the frequency would be five cycles per second ($f = 5$ Hz), the pulse width 40 ms and the duty cycle (dc) 20%.

fish swimming over a stationary wire-shaped electrode pair will be exposed to varying electric field strengths, experiencing maximum intensity when located closest to the electrodes. If a moving electrode array is used, as in commercial fishing practice, the exposure will also depend on the location of the animal relative to the electrodes plus its ability to move during exposure. For example, pulse trawling using an immobilizing stimulus such as the cramp pulse for common sole, allows for calculation of the maximal total exposure time by dividing the length between the start of the first and the end of the last electrode element by the towing speed of the gear relative to the bottom. However, this may be much shorter if the animal is exposed in the periphery of the electric field or exposed to a startle pulse and able to escape the electric field. Besides, the exact exposure intensity depends on the location and orientation of the organism with respect the electrodes. An electrode array consisting of multiple electrodes, moving faster than the organism is able to escape, will expose the animal to a complex pulse train consisting of different short exposures, each of them rising and waning in strength (de Haan *et al.*, 2016).

Electrical waveform parameters

Two main types of electric current exist: DC and AC. However, to cope with the high energy demand in high conductivity environments such as seawater, a series of short electrical pulses instead of continuous current flow are used for electric pulse trawling. In marine electrofishing, pulses are often produced by using a capacitor to accumulate and then quickly discharge electric current. Hence, the same peak power that is delivered in a continuous DC waveform is now released during a pulse with a shorter duration, thus reducing mean power demand. The resulting waveform is a PDC but PBC and pulsed alternating current (PAC) can be delivered when H-bridges are used to switch connection between the two electrode arrays.

Terminology used for describing electrical waveform parameters

Pulsed electrical waveforms are characterized by recurring patterns of individual pulses of current. The complete sequence intervening between two successive corresponding points in that pattern is termed the cycle of the waveform. In pulsed currents the distinction should be made between the "cycle" (see definition above) and an individual "pulse," i.e. a single pulse of electrical current, which may encompass a complete cycle (in PDC waveforms) or be a part of it (in AC, PBC, and PAC waveforms). PDC, PAC, and PBC waveforms can be described by electrical pulse parameters illustrated in Figure 4 and defined in Table 1.

In previous pulse trawling research, PAC has been used to refer to the waveform type where the polarization reversal occurred (almost) immediately followed by a long (inter pulse) interval time, whereas PBC was used when the interval time between the polarization reversal was equal (Figure 5) (Soetaert *et al.*, 2016a, b). We propose to make the distinction threshold between PAC and PBC based on the length of the pulse width (PW) and pulse break time (PB). All bi-directional waveform types of which the shortest PB exceeds the longest PW, should be referred to as PBC, and otherwise as PAC. This approach clarifies the difference between both waveform types, but it does not overcome inherent confusion about the pulse width and break time variations. Therefore, we recommend to include pulse width and pulse interval time/break time in the name of the applied waveform type, especially when different waveform types are used and discussed in the same study. This should be done by firstly indicating the pulse width, followed by the break time between brackets. The pulse followed by the shortest PB is considered the first with its PW and following PB referred to as PW_1 and PB_1, whereas the next pulse PW and PB are referred to as PW_2 and PB_2 (Figure 5c). In case of PAC, 40 Hz PAC ($PW = 0.2$ and 0.3 ms, $PB = 0.1$ and 24.4 ms) is a bi-directional waveform of which each period consists of a 0.2 ms pulse, a 0.1 ms interval, a 0.3 ms pulse from the opposite polarity, and a 24.4 ms interval (Figure 5c). In case of PBC, 40 Hz PBC ($PW = 0.3$ and 0.2 ms, $PB = 12.25$ and 12.25 ms) is a bi-directional waveform of which each period consists of a 0.3 ms pulse, a 12.25 ms interval, a 0.2 ms pulse of opposite polarity, and another 12.25 ms interval, as illustrated in Figure 5d. In case both pulse widths and/or both interval times have the same duration, it suffices to give the value once. For example, PBC ($PW = 0.25$ and 0.25 ms, $PB = 12.25$ and 12.25 ms) can be rewritten as PBC ($PW = 0.25$ ms, $PB = 12.25$ ms) and PAC ($PW = 0.25$ and 0.25 ms, $PB = 0$ and 24.5 ms) as PAC ($PW = 0.25$ ms, $PB = 0$ and 24.5 ms) (Figure 5e). Although only indispensable for a concise but clear notation of PAC and PBC, this can also be applied to PDC. For example, pulse type 80 Hz PDC ($PW = 0.25$ ms, $PB = 12.25$ ms) (Figure 5a). In addition, it is also proposed to introduce the total pulse width (PWt) as the time interval in PAC covering both pulses: $PWt = PW_1 + PB_1 + PW_2 = T - PB_2$ (Figure 5b and c).

Table 1. Overview of electrical pulse parameters with their symbol, unit, and definition.

	Pulse parameter	Symbol	Unit	Definition
Key parameters	Amplitude	V	Volt, V	Maximum potential difference or field strength of a pulse. This can be circuit or location specific and be expressed as peak voltage, peak-to-peak voltage, median voltage, or root mean square voltage.
	Frequency	f	Hertz, Hz	Number of cycles per second
	Pulse width	PW	Millisecond, ms	Time duration of a single pulse during which the circuit with electrodes is charged
	Pulse shape	PS	–	Shape of a single pulse which can be, e.g. exponential decay, sinusoidal, or rectangular (see Snyder, 2003)
Amplitude parameters	Peak voltage	V_{pk}	Volt, V	Magnitude of the zero to maximum (or minimum) instantaneous voltage appearing between the electrodes. If a poorly formed waveform is used with an initial voltage overshoot (Figure 4) then V_{pk} will reflect this value. If using bipolar pulses, which have positive and negative peaks with different amplitudes, the highest absolute value should be given.
	Peak-to-peak voltage	V_{pk-pk}	Volt, V	Potential difference between the maximum and minimum instantaneous voltage appearing between the electrodes. For PDC (with no negative component), V_{pk-pk} will equal V_{pk} since all peaks have the same polarity and are measured against the baseline. For alternating/bipolar pulses, V_{pk-pk} is the potential difference between the positive and negative peak voltage: $V_{pk-pk} = V^{+}_{pk} - V^{-}_{pk}$.
	Median voltage	V_{med}	Volt, V	Voltage measured in the middle of a pulse, i.e. at half the PW. Although this value does not properly represent the energy content, it is easy and straightforward to interpret and determine for rectangular pulse shapes. It also diminishes the impact of voltage overshoot at the onset or end of the pulse and gives a measure of pulse stability or decay.
	Root mean square voltage	V_{rms}	Volt, V	Equal to the value of DC voltage that would produce the same power dissipation in a resistive load
Time related parameters	Duty cycle	dc	Percentage, %	Calculated as $dc = ((PW \times f)/1000) \times 100$ for PDC or $dc = (((PW_1 + PW_2) \times f)/1000) \times 100$ for PAC and PBC with the PW in milliseconds and frequency (f) in Hz
	(Inter pulse) interval time or pulse break time	PB	Millisecond, ms	Time span between two pulses, measured from the end of the fall time to the onset of the rise time of the next pulse
	Period	T	Millisecond, ms	Time from the start of one cycle to the start of the next cycle, i.e. 1 s/f
	Pulse period	PT	Millisecond, ms	Time from the start of one pulse to the start of the next pulse, i.e. $PW + PB$. Note that for PDC, $PT = T$
	Rise time	δt_{rise}	Millisecond, ms	Time it takes the pulse to rise from 10 to 90% of V_{med}
	Fall time	δt_{fall}	Millisecond, ms	Time it takes the pulse to fall from 90 to 10% of V_{med}
Other parameters	Total pulse width	PW_t	Millisecond, ms	Time interval in PAC covering both pulses $PW_t = PW_1 + PB_1 + PW_2 = T - PB_2$
	Apparent frequency	f_a	Hertz, Hz	Number of PBC pulses per second
	Burst width	BW	Millisecond, ms	Time duration that a GB pulse is present starting from the onset of the first pulse until the offset of the last pulse of the burst
	Burst interval/break time	BB	Millisecond, ms	Time interval between two bursts of a GB

Gated bursts

Pulsed electrical waveforms can also be provided as gated bursts (GBs). These are complex pulse stimulations consisting of short series of higher-frequency pulses (referred to as bursts) delivered at a lower secondary frequency as illustrated in Figure 6. This pulse stimulation type is claimed to reduce the incidence of spinal injuries in freshwater electrofishing by inserting periods with reduced pulse stimulation allowing for the relaxation of the muscles (Snyder, 2003). It also considerably reduces the mean power demand (i.e. Vrms, Arms) of the output. We suggest application of a similar approach as shown above to describe GB by using the concept of burst width (BW, [milliseconds, ms]), expressed as the time duration that the pulse is present starting from the onset of the first pulse until the offset of the last pulse of the burst, and burst interval/break time (BB, [milliseconds, ms]), i.e. the interval time between two bursts (Figure 6). For example, a pulse train of 5 Hz, with each series of pulses containing 5 DC pulses at a frequency of 100 Hz (PDC ($PW = 0.2$ ms, $PB = 9.8$ ms)) followed by a 159.8 ms break would be named GB ($PW = 0.2$ ms, $PB = 9.8$ ms and $BW = 40.2$ ms, $BB = 159.8$ms) (Figure 6).

Physiological relevance of unambiguous waveform parameter definitions

Confusion can arise when comparing PAC and PBC results since the frequency can be interpreted differently. Indeed, the physiological effect of the 20 Hz PBC is similar to that of the 40 Hz PDC, assuming the same voltage and duty cycle, because the neuromuscular system will experience 20 negative pulses plus 20 positive pulses (i.e. 40 individual pulses) per second. When aiming to induce muscle cramp, the temporal summation of electrical stimuli determines the contractive force. Some studies focusing on physiological effects therefore listed the PBC frequency as the number of individual pulses as this was most relevant to compare

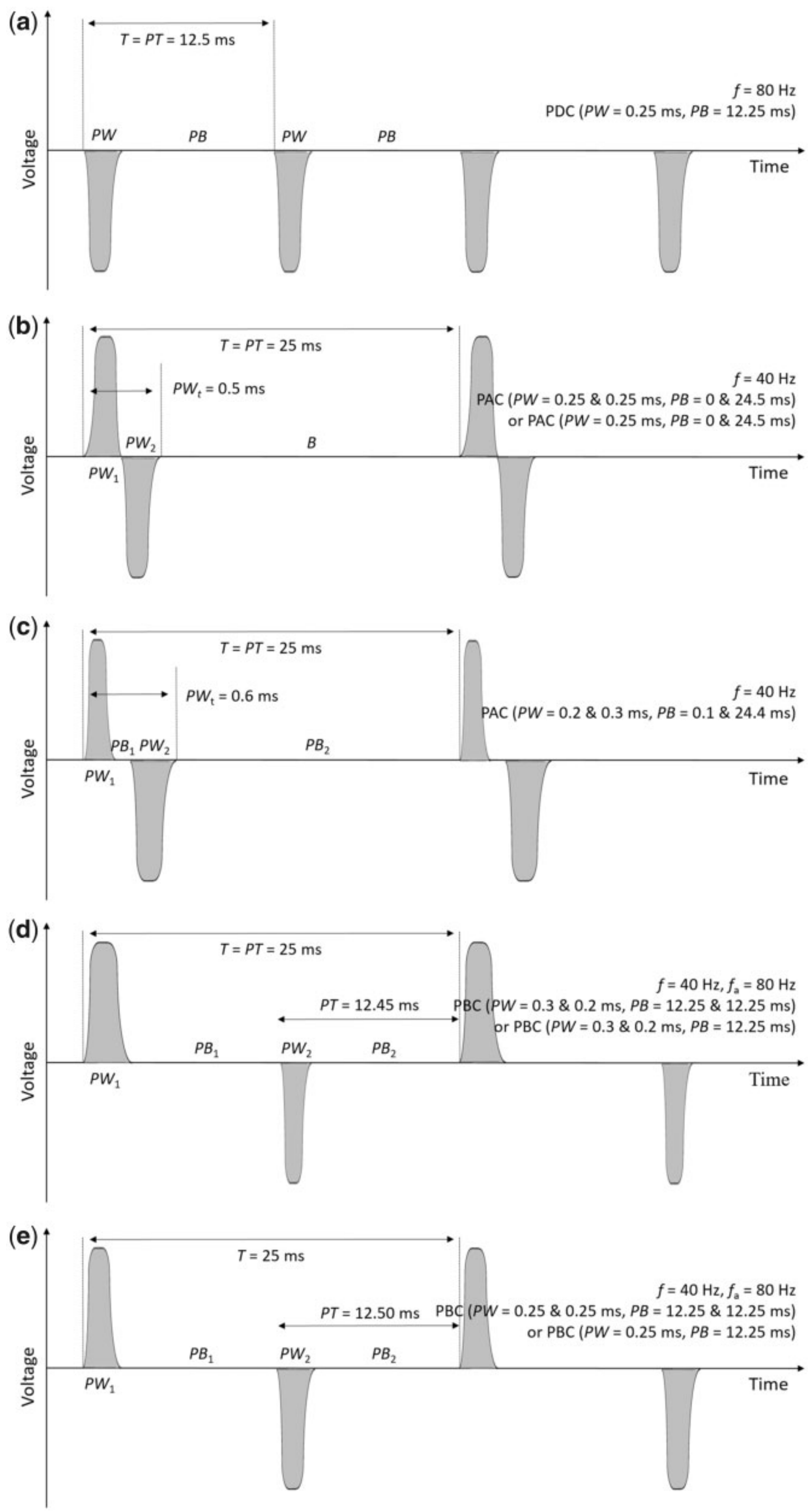

Figure 5. Schematic representation of (a) PDC; (b) and (c) PAC; and (d) and (e) PBC waveforms to illustrate the pulse parameters and pulse names. Each depicted pulse stimulus (not on scale) has a duty cycle of 2%. The indicated pulse parameters are pulse width (PW), total pulse width (PW_t), pulse break time (PB), period (T), pulse period (PT), pulse frequency (f), i.e. the number of cycles per second, and the apparent frequency (fa), i.e. the number of PBC pulses per second. The legend right above each *x*-axis indicates the frequency as well as the recommended name to describe that specific waveform.

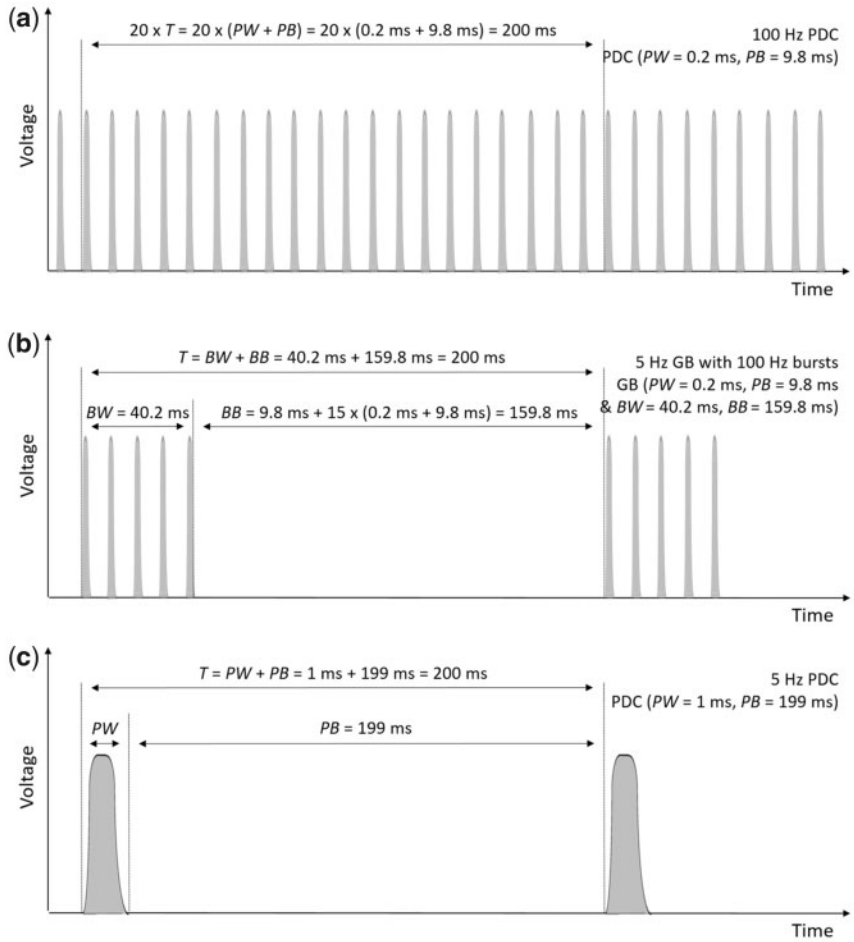

Figure 6. Schematic representation of a 100 Hz PDC (a) used to generate the GBs (b) and a 5 Hz PDC with the same period (T) as the GB (c). The indicated waveform parameters are pulse width (PW), burst width (BW), inter pulse interval or break time (PB) and burst break time (BB). The legend in the top right corner of each graph indicates the frequency (f) as well as the recommended name to describe the specific waveform. The 100 Hz PDC has a duty cycle of 2% whereas the GB and 5 Hz PDC both have a duty cycle of 0.5%.

responses between PDC, PAC, and PBC (Soetaert *et al.*, 2016a, b) because a 20 Hz PBC ($PW = 0.25$ ms, $PB = 12.25$ ms) with 40 pulses per second would induce tetany whereas a 20 Hz PDC ($PW = 0.5$ ms, $PB = 12$ ms) or 20 Hz PAC ($PW = 0.25$ and 0.25 ms, $PB = 0$ and 24.5 ms) would not. However, this frequency was incorrect and should have been divided by two, since frequency is expressed as the number of unique cycles per second, i.e. each repetition of a positive and a negative pulse. Hence, we suggest to differentiate between frequency (f), i.e. the number of cycles per second, as defined by the International System of Units (Figure 5d and e), and the "apparent frequency" (fa), i.e. the number of individual PBC pulses per second. The apparent frequency of a PBC frequency of 20 Hz would therefore be 40 Hz (Figure 5). If not specified, "frequency" should always refer to the number of cycles per second.

Standardizing study design descriptions in laboratory, computational, and field set-ups

The intensity of the electric field at a certain location depends on many factors such as the electrode characteristics, tank configuration, stream characteristics, position of the animal, animal body plan and characteristics, and the specific waveform parameters used, as seen in previous chapters. Hence, clear and complete descriptions of the field or experimental set-up designs are required for qualitative and quantitative repetition of results. Table 2 gives a guideline to do so in a standardized way indicating what information should be provided recommended or optionally. The minimum elements needed to recreate the experiment are given in the column "Recommended" whereas other items of interest are given in column "Optional."

Although the use of an oscilloscope image is not strictly necessary, it is highly recommended to include when presenting data because it helps to visualize and check the waveform parameters used. Ideally this should consist of two parts: an overview of the waveform on a time frame of $\sim$1 s (Figure 7a) and a close-up of a single pulse (Figure 7b) on which the time and voltage intervals are given. In case of a GB, a third figure showing one entire burst cycle is recommended. Additionally, other relevant waveform and pulse parameters, as well as their values measured by the oscilloscope, can be indicated in the image or caption.

Table 2. Overview of information to be provided when describing an electrofishing set-up for experimentation.

	Recommended	Optional
Generator equipment	• Manufacturer • Model number • Rated power output	○ Supply type (mains and generator) ○ Supply output (volt and ampere) ○ Presence of e.g. capacitors, inductors, and H-bridges
Electrode array(s)	• Dimensions and number of electrode (array)s and insulators • Construction material • Positioning in tank or fishing gear • Distance apart (height or linear distance)	○ Description of equipment used to position the electrodes in the tank ○ Figure of the electrode set-up
Water characteristics	• Water depth • Conductivity (ambient or specific) • Temperature	○ Salinity ○ Dissolved oxygen ○ pH ○ Ammonia, nitrite, nitrate
Experimental tank	• Dimensions • Construction material • Porosity/particle size of bottom substrate • Depth of bottom substrate • Construction of any fish holding device/net • Schematic drawing and/or photo of set-up	○ Presence of other (conducting) objects/materials in tank such as filtration tubing and pumps ○ Electric field characteristics (homo- or heterogeneous)
Experimental animal	• Species • Acclimatization period in tank • Orientation of the animal relative to the electrodes • Animal size and mass • Anaesthetics: use, type, and dose	○ Origin of animal (wild/reared) ○ Animal sex ○ Reproductive stage (e.g. immature, mature, or gravid) ○ Any feeding regime ○ Number of animals exposed simultaneously ○ Presence and location of wounds/lesions/malformations (prior and/or after experiment/electrical exposure) ○ Number of vertebrae
Waveform parameters	• Waveform type: PDC, PBC, PAC, or GB • Pulse shape • Pulse frequency • Pulse and/or burst width • Pulse amplitude (e.g. *V*pk, *V*pk–pk, *V*rms) • Pulse exposure duration	○ Duty cycle ○ Pulse or burst break/interval time ○ Pulse rise time ○ Pulse fall time ○ Oscilloscope image of waveform

The minimum elements needed to recreate the experiment are given in the column "Recommended" whereas other items of interest are given in column "Optional."

Finally, we also suggest standardizing the usage of measurement units but these are not restrictive and may be adjusted, depending on the area of interest, to achieve the appropriate descriptions. For example, expressing voltage gradient in V m^{-1} is common practise in marine electrotrawling, due to lower voltage gradients used, in contrast to freshwater electrofishing, wherein V cm^{-1} is more widely adopted since relatively larger voltage gradients are used.

Concluding discussion

The current paper defines key aspects relevant to marine electrotrawling and the use of appropriate abbreviations/symbols and units. The aim was to provide information on the physiological effects on organisms and physical parameters of electrical (pulse) stimulation, explain associated electrical parameters, and provide best-practice recommendations for presenting and publishing results in this field. Together these guidelines will eliminate unclear or contradictory use of waveform parameters and harmonize descriptions and terminology. We hope they will enable qualitative and transparent discussions and comparisons, and facilitate accurate repetition of electrofishing experiments. In addition, these guidelines will provide a concise and comprehensible manual for those not familiar with this topic.

The need for this reference work was expressed by the Working Group on ELECtrical TRAwling (WGELECTRA) of the International Council for the Exploration of the Sea (ICES). WGELECTRA recommends these guidelines as a consistent approach to better communication standards in electrofishing, and pulse trawling in particular. In addition, we believe that these guidelines are also useful for freshwater electrofishing studies and hope it will promote closer collaboration between these, currently insufficiently intertwined, research fields. Hence, this summary aimed to incorporate existing terms and abbreviations from both freshwater and marine electrofishing.

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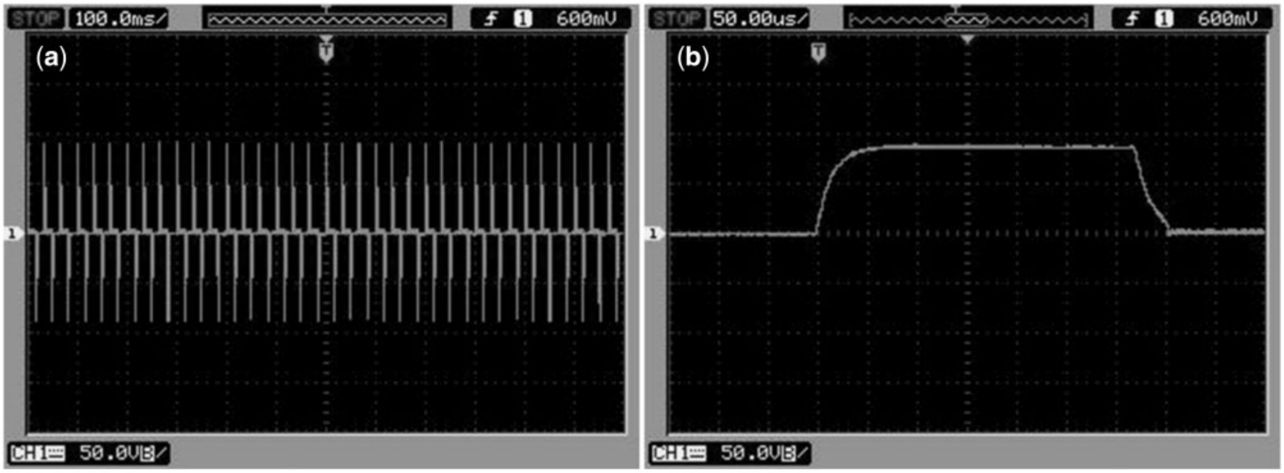

Figure 7. An overview of the same square wave or rectangular electrical pulse stimulus plotted at a time frame of 1.2 s (12 × 100.0 ms) (a) and 0.6 ms time frame showing the single pulse (12 × 50.0 µs) (b). This pulse stimulus was generated in seawater using the following settings: frequency (f) = 30 Hz, amplitude = 85 V and pulse width (PW) = 0.33 ms. The graphs show the measurements taken on the electrodes in the water indicating 3 cycles per interval of 100.0 ms or 30 cycles per second (Hz) and a rise time (δt_{rise}) and fall time (δt_{fall}) of 0.05 and 0.03 ms, respectively. The pulse width is 0.35 ms instead of the set 0.33 ms which is due to the extended fall time sometimes caused by certain electrical circuits or pulse generators, which illustrates the importance of verifying the output pulse parameters by means of an oscilloscope.

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