Aquaculture 434 (2014) 277–281

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Short communication

Preventing injuries and recovery for electrically stunned Atlantic salmon (*Salmo salar*) using high frequency spectrum combined with a thermal shock

Endre Grimsbø [a,b,*], Ragnar Nortvedt [a], Erling Hammer [c], Bjorn Roth [d]

[a] University of Bergen, Department of Biology, Thormøhlensgate 53, Box 7803, N-5020 Bergen, Norway
[b] Institute of Marine Research, Box 1870 Nordnes, N-5817 Bergen, Norway
[c] University of Bergen, Department of Physics and Technology, Allégaten 55, N-5007 Bergen, Norway
[d] Nofima AS, Department of Processing Technology, Box 8034, N-4068 Stavanger, Norway

ARTICLE INFO

Article history:
Received 22 May 2014
Received in revised form 25 June 2014
Accepted 15 July 2014
Available online 10 August 2014

Keywords:
Atlantic salmon
Electronarcosis
Injuries
Unconsciousness
Frequency spectrum
Fish brain

ABSTRACT

To understand the importance of electrical frequencies on stunning, recovery and inflicting injuries, Atlantic salmon (*Salmo salar*) were exposed for 5 s to either 217 V, 50 Hz, AC or 107 V coupled AC + DC at 200 Hz, containing a high frequency spectrum or not. Post stun the fish were placed back into water, either at ambient seawater temperature (10.4 °C) or cold water (−1.3 °C), to look upon recovery or mortality. Results show that a high frequency spectrum at low decibels prevents the muscles from contracting in such a degree that spinal injuries and haemorrhaging were prevented in all individuals. Injury rates of 14 and 18% were observed when using electrical signals containing only low frequencies of 200 Hz AC + DC and 50 Hz, AC. The high frequency spectrum also reduced the stimulation of the brain as fish recovered faster with no mortality. Adding a cold shock post stunning delayed or prevented recovery of all groups within the time span required to kill the fish by exsanguination.

1. Introduction

In Norway, electrical stunning has become the most common stunning method for slaughtering Atlantic salmon (*Salmo salar*). Atlantic salmon are dry stunned using approximately 110 V, coupled AC and DC, where the fundamental frequency of the AC component is approximately 200 Hz analogous to a 50 Hz AC (Lambooij et al., 2010). This is not without risks. Spinal injuries and haemorrhaging in the muscle are common problems with electrical stunning for both farmed fish (Robb et al., 2003; Roth et al., 2003) and poultry (Kranen et al., 1998a, 1998b, 1999, 2000). For fish, the susceptibility for spinal injuries is mainly due to strong muscle contractions during electric exposure depending on the stamina (Roth et al., 2004) and the strength of the vertebrae. Fish like Atlantic salmon (Roth et al., 2003), rainbow trout (*Oncohynchus mykiss*) (Lines et al., 2003), herring (*Clupea harengus*) (Nordgreen et al., 2008) and saithe (*Pollachius virens*) (Roth et al., 2004) are particularly vulnerable, while injuries have not been reported for Atlantic cod (*Gadus morhua*) (Digre et al., 2010) and turbot (*Scophthalmus maximus*) (Lambooij et al., 2013; Morzel et al., 2003). The strength of muscle contraction is highly dependent on the current frequency with the maximum contraction rate in the range similar to that recommended for electro-stunning of several species (Jones et al., 1979; Rattay, 1990; Solomonow, 1984a,b; Takata and Ikata, 2001), which also reflects the probability to inflict injuries to both fish (Lines et al., 2003; Roth et al., 2004) and poultry (Mouchonière et al., 1999; Raj, 2006). Analogous to the muscles, brain stimulation is dependent on the current frequency whereas higher frequencies are less efficient for rendering the animal unconscious (Lines et al., 2003; Robb et al., 2002; Roth et al., 2004; Terney et al., 2008). In combination frequencies, the stun duration and mortality are also related to the magnitude and duration of the current (Lines et al., 2003; Robb et al., 2002). From a welfare and quality perspective, this is challenging since an efficient current frequency for stunning fish represents a potential risk for injuries and vice versa (Lines et al., 2003; Roth et al., 2004).

One solution seems to use multiple frequencies, where the fundamental frequency falls into the most efficient range for stunning of 200 Hz. This waveform has been proven to work properly on Atlantic salmon since all the fish that went through the system are reported to be without injuries (Lambooij et al., 2010; Roth et al., 2009). In order to understand the effect frequency spectrum has on the brain and

* Corresponding author at: Institute of Marine Research, Box 1870 Nordnes, N-5817 Bergen, Norway. Tel.: +47 916 09 034.
E-mail address: endre.grimsbo@imr.no (E. Grimsbø).

http://dx.doi.org/10.1016/j.aquaculture.2014.07.018
0044-8486/

muscle, it is important to consider the released action potentials in the nerve cells. The nerve cell might be described as a power cable, with the nerve fibre as a cylindrical structure (Hodgkin and Huxley, 1952; Taylor, 1963). By using the cable model, electrical theory can reveal the mechanisms that control the action potentials (Rattay, 1990; Tasaki and Matsumoto, 2002) and thereby a good approach for simulating nerve signals (Narayanan, 2007; Rattay, 1990; Solomonow, 1984a).

From an evidence-based perspective, it is interesting to understand why a frequency spectrum can prevent the muscle from heavy contractions by blocking some part of the nerve signal (Rattay, 1990; Solomonow, 1984a,b) while stimulating the brain into the state of unconsciousness (Lambooij et al., 2010). High frequency spectrum has shown that unconsciousness of fish can be stimulated within 0.5 s (Lambooij et al., 2010). The duration of the unconscious condition and related mortality is challenging and dependent on the magnitude and duration of the current (Lines et al., 2003; Robb and Roth, 2003; Robb et al., 2002; Roth et al., 2003), whereas the optimum current duration for quality is 5 s and below (Roth et al., 2010). This will cause the animal to recover during exsanguination (Lambooij et al., 2010). Research on other fish species shows that a thermal shock after an electrical stun will prevent the fish from recovering (Lambooij et al., 2006, 2013).

The aim of this study was therefore to investigate the importance of a high frequency spectrum for preventing injuries in Atlantic salmon followed by a thermal shock to see if recovering could be prevented.

2. Materials and methods

The experiments were performed in December 2008 at Grieg Stjernerlaks, Helgøy at the southwest coast of Norway. A total of 64 market sized Atlantic salmon (*S. salar*) (≈4.5 kg) were used. The fish were kept in waiting net cages near the slaughter house. The sea temperature was 10.4 °C.

The experiments were conducted by exposing one fish at a time either for a coupled AC/DC signal, with a fundamental frequency of 200 Hz and 107.0 V, or 106.5 V RMS (Lambooij et al., 2010). At 107.0 V, an unfiltered signal (groups *A* and *B*, Table 1) was used whereas a filtered signal at 106.5 V, (groups *C* and *D*) which is the higher part of the frequency spectrum, was removed.

The coupled signal at 200 Hz was generated by a Stansas01™ electro-stunner (Seaside A/S, Stranda, Norway). After stunning, the fish were stored in a factory design and placed into an aquarium containing either −1.3 or 10.4 °C seawater to look upon the time of recovery and mortality. As a control, one group of fish was exposed to 217.2 V RMS, sinusodial 50 Hz AC signal. A time relay was used for all groups to produce a uniform length of the stunning signal equal to 5 s.

2.1. Experimental setup

To get accurate current and frequency readings, one plate electrode (stunning shoe) was attached to the fish's head with the whole body on the other electrode (Fig. 1). Fig. 1 describes the filter, which consists of coils and capacitors. A NI PXI-4071 Digital Multimeter (National Instruments Corporation, Austin TX, USA) was applied for voltage measurements at 700 kS/s over the electrodes (Fig. 1) to measure the frequency spectrum. The frequency spectrum was analysed by dedicated software (LabVIEW), based on Fast Fourier Transform (FFT) analyses (Brigham and Morrow, 1967). The Hanning window (Testa et al., 2004) function in LabVIEW with default parameters reduced the FFT analyses' spectral leakage. The frequency spectrum was analysed before (Fig. 2) and after (Fig. 3) filter modification. By adding capacitors and coils to the system, the frequency spectrum (Fig. 2) was manipulated until the high-frequency part was removed (Fig. 3).

Voltage measurements and ampere RMS values were carried out with a 20 MHz, FLUKE 123™ industrial scope meter (Fluke Inc, Everett WA, USA). A FLUKE 80i-110s AC/DC current probe (Fluke Inc, Everett WA, USA) was connected to the industrial scope meter and pinched on the wiring between Coil 1 (Fig. 1) and the stunning shoe to measure the electrical current. The voltage was measured by a regular voltage probe connected to the industrial scope meter. Some RMS values are incomplete in each group due to difficulty in reading the scope meter. A laptop recorded the measurements from the scope meter through FlukeView ScopeMeter Software for Windows SW90W (B.V. Tilburg, The Netherlands).

2.2. Recovery

After electric exposure, the vestibulo-ocular reflex (VOR) method or eye roll was used to determine whether the animal was stunned unconscious (Kestin et al., 2002). The fish were placed into a 1 m^3 aquarium either at costing ambient (10.4 °C) or −1.3 °C seawater and then recovery or mortality was evaluated by monitoring the time until the start of ventilation, movement and regaining equilibrium (Roth et al., 2003) in addition to VORs (Kestin et al., 2002).

The maximum evaluation time was 1200 s. If the fish did not start ventilation within 1200 s, they were considered dead. After 1200 s the fish were killed by percussive blow to the head, exsanguinated and

Table 1
Mean fish weight, length, volt, ampere, ventilation delay, recovery time, consciousness, mortality and damage (±SD) in Atlantic salmon after stunning with a Stansas 01 electro stunner, with or without filter that removed the high-frequency part of the signal, or after stunning with a 50 Hz transformer. The fish were then placed in ambient or ice water for recovery. The electro-stunner's setting was equal for all the fish, but the voltage and ampere RMS values were only measured for a sample of each fish group. Mortality represents the numbers of fish of the sample that did not recover with a delayed ventilation response after 10 min, so were considered dead. Fish that recovered with ventilation response are presented by time delay from stunning. The number of fish that fully recovered, including their recovery times are given. Injured fish of total, stunned [a]without filter, [b]with filter, and [c]with 50 Hz transformer. None of the fish in group *D* recovered within 1200 s.

	Stansas 01				Transformer
	Without filter		With filter		50 Hz
Group:	A	B	C	D	E
	Ambient (10.4 °C)	Ice (−1.3 °C)	Ambient (10.4 °C)	Ice (−1.3 °C)	Ambient (10.4 °C)
Fish weight (kg):	3.85 ± 1.31 (n = 10)	4.14 ± 2.02 (n = 15)	5.00 ± 1.44 (n = 11)	4.82 ± 1.30 (n = 11)	5.01 ± 2.31 (n = 10)
Fish length (cm):	68.8 ± 6.9 (n = 10)	70.1 ± 9.4 (n = 15)	73.5 ± 4.3 (n = 11)	72.4 ± 6.6 (n = 11)	72.9 ± 7.95 (n = 10)
Volt (RMS):	106.4 ± 1.7 (n = 7)	108.3 ± 1.1 (n = 13)	107.1 ± 0.9 (n = 7)	106.0 ± 1.2 (n = 9)	217.2 ± 1.2 (n = 8)
Ampere (RMS):	0.78 ± 0.09 (n = 10)	0.94 ± 0.44 (n = 15)	0.62 ± 0.26 (n = 7)	0.70 ± 0.30 (n = 11)	1.96 ± 0.54 (n = 9)
Ventilation delay (s):	106 ± 38 (n = 10)	136 ± 68 (n = 7)	250 ± 152 (n = 6)	350 ± 133 (n = 5)	
Fully conscious recovery time (s):	184 ± 81 (n = 9)	311 ± 123 (n = 7)	373 ± 153 (n = 3)	>1200*	
Fully conscious (#):	9 of 10	7 of 15	3 of 11	0 of 11	
Mortality (#):	0 of 10	8 of 15	5 of 11	6 of 11	
Fillet damage (blood spots) (#):	0 out of 22[a]		3 out of 22[b]		3 out of 17[c]