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Effect of Electric Field Strength and Current Duration on Stunning and Injuries in Market-Sized Atlantic Salmon Held in Seawater

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Abstract.—We evaluated electricity as a stunning method before slaughter of Atlantic salmon *Salmo salar* by assessing both stunning effectiveness and injuries. About 300 salmon (1.2–6.6 kg) were exposed to one-phase, sinusoidal, 50-Hz AC in seawater; electrical field strengths ranged from 15 to 250 V/m and current durations from 0.2 to 12 s. We measured the duration of the epileptic-like seizures after stunning and the degree of unconsciousness based on behavioral responses. Fish were killed, bled, and gutted 10 min after stunning and then analyzed for injuries. The proportion of fish sufficiently stunned, the duration of an unconscious condition, and the occurrence of broken vertebrae and hemorrhages were all dependent on electric field strength and current duration. The electric field strength required to stun the fish was inversely proportional to the current duration, dropping from 200 V/m at 0.8 s to 25 V/m at 6–12 s. Electricity proved to be efficient in stunning fish, but to avoid injuries in market-sized Atlantic salmon the current duration should be less than 1.5 s at field strengths ranging from 125 to 150 V/m.

In Norway, farmed fish such as Atlantic salmon *Salmo salar* and rainbow trout *Oncorhynchus mykiss* are stunned with carbon dioxide (CO_2) before slaughter. Fish respond to the hypoxic environment by initiating secondary stress responses that result in an exhaustive struggle lasting 3–4 min (Yokoyama et al. 1993; Marx et al. 1997; Roth et al. 2002). This premortem stress produces an earlier onset and resolution of rigor mortis (Thomas et al. 1999), softer flesh texture (Nakayama et al. 1992; Roth et al. 2002), gaping (Dunajski 1979; Lavèty et al. 1988), and reduced shelf life (Lowe et al. 1993). Use of electricity for stunning as a possible alternative to CO_2 would have advantages, including instant immobilization and inhibition of secondary stress responses before slaughter, which would thereby improving flesh quality (Roth et al. 2002). Pulsed DC (PDC) or AC can affect the central nervous system of fish, producing a state of trauma termed electronarcosis (Lamarque 1990). However, AC and PDC can produce dislocations and fractures of the vertebrae (Hauck 1949; Sharber and Carothers 1988; Sharber et al. 1994; Habera et al. 1996; Ainslie et al. 1998), as well as hemorrhages and rupture of the dorsal arteries (Spencer 1967; Hollender and Carline 1994). In commercial fish processing, such as the smoking industry, these injuries are not acceptable because blood clots in fillets would decrease flesh quality and, thus, reduce market value (Michie 2001).

Injuries are caused by heavy muscle contractions induced by electrical stimulation of the neuromuscular system by AC, PDC, or DC (Reynolds and Kolz 1988; Lamarque 1990). Field strength (Spencer 1967; McMichael 1993), current frequency (McMichael 1993; Sharber et al. 1994), and pulse shape (Sharber and Carothers 1988) also affect the degree of injury. It is unclear which electrical features are optimal for stunning fish. Lamarque (1990) suggested that use of high frequencies (up to 2000 Hz) could prevent injury-causing muscle contractions, but Sharber et al. (1994) indicated that high frequencies stimulate epileptic seizures, causing injuries. The effect of field strength and frequency have been studied in this context, but research on the effects of the electric duration have been limited. It is generally assumed that the electric duration can effect injuries (Lamarque 1990; Sharber et al. 1994). However,

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Spencer (1967), found no apparent relationship between current duration and incidence of injured vertebrae, noting that fractures or dislocations of vertebrae occur immediately upon the electric exposure.

Using one-phase, sinusoidal, 50-Hz AC in seawater, we examined the effects of electric field strengths and current durations on stunning effectiveness and injuries in Atlantic salmon harvested for market.

Methods

Experimental unit.—We used one-phase, sinusoidal, 50-Hz AC because the equipment is readily available and, unlike DC, effectively induces electronarcosis (Lamarque 1990). The potential difference (in V) was regulated using an autotransformer: maximum 25 A from 0 to 250 V root mean-square (V_{rms}). The duration of current (0.2–12 s) was regulated with a time relay. The experimental unit consisted of a Plexiglas tank (150 × 30 × 35 cm) in which the electrodes were 100 cm apart. Each electrode consisted of several horizontally aligned 0.5-cm-diameter steel rods held 2.5 cm apart, which created a homogeneous electric field. The total resistance of the experimental unit was approximately 4 ohms. To protect the salmon from direct contact with the electrodes, plastic walls filled with small holes were placed in front of the electrodes. The fish were always facing the electrodes before stunning. Water was pumped from a 40-m depth to provide a constant temperature of 7–8°C and salinity of 30–34‰. Water in the experimental unit was changed frequently to avoid oxygen deficiency.

Experimental setup.—A total of 276 immature salmon (1.2–6.6 kg) were randomly removed from a resting pen and transferred to a container (1 × 1 × 1 m) with circulating seawater, where they were allowed to rest for a minimum of 2 h before electrical stunning. First, to establish the electrical metrics that were able to stun the fish, salmon were individually exposed to a specific electric field strength ranging from 25 to 250 V_{rms}/m at intervals of 25 V_{rms}/m. The electric duration was set to 0.2–12 s. These results were used to design another experiment where replicates from 10 to 25 salmon were exposed to current durations ranging from 1 to 6 s and field strengths from 25 to 200 V_{rms}. Electrical measures that did not stun the first two fish were not used in further experiments.

In each experiment several behavioral responses were observed after the fish was stunned. The initial epileptic-like response (seizure) was divided in a clonic phase (vigorous thrashing from side to side) and a tonic phase (a slight shiver). After this seizure, several stages of behavior were noted that described the stages of unconsciousness, as described in Table 1. To calculate the duration of unconsciousness stages 3 and 4 were used. The fish were removed within 20 min, and their ventricular heart activity was assessed by cutting off one set of gill arches and observing blood flow. Fork length and weight were measured before the fish was marked and gutted. The salmon were stored for 2 or 3 d on ice and then filleted and examined for possible injuries. Hemorrhages were observed as blood clots in the fillet or along the spinal column; vertebrae were also examined for visual fractures. A control group of 20 fish were killed by a sharp blow to the head to see if injuries could be caused by physical treatment.

Statistical analysis.—To evaluate the relation between the duration of the unconscious condition and independent variables such as field strength, current duration, and fish length, multiple regres-

TABLE 1.—Modified protocol from Burka et al. (1997) to determine, based on behavioral observations of Atlantic salmon, different stages (0–5) of reaction to electrical exposure. Behavioral studies were based on signs of swimming activity, reactivity to visual and tactile stimuli, equilibrium efforts, and ability to ventilate.

Stage	Description	Behavioral signs
0	Normal	Active swimming patterns
		Normal reactivity to visual and tactile stimuli
		Normal equilibrium
		Normal ventilation of operculum
1	Light sedation	Reduced swimming activity
		Slight loss of reactivity of visual and tactile stimuli
		Problems with equilibrium
		Normal ventilation of operculum
2	Light narcosis	Weak swimming activity
		No reactivity to visual stimuli
		Weak reactivity of tactile stimuli
		Slow and long ventilation rate
		Equilibrium loss with efforts to right
3	Deep narcosis	No swimming activity
		No reactivity to visual stimuli
		Barely reactivity to strong tactile stimuli
		Problems of ventilation of operculum
		Total loss of equilibrium
4	Surgical anesthesia	No swimming activity
		No reactivity to visual or strong tactile stimuli
		Ventilation ceases
		Total loss of equilibrium
5	Medullary collapse	Death ensues

sion analysis was used as the statistical model. Fish that were either improperly stunned or died during the experiment were excluded from the multiple regression analysis. To meet the assumptions of linearity and normal distribution of residuals, all variables were square-root-transformed. Partial correlation of all variables was used to reveal correlation between the independent and dependent variables. Assuming that field strength and current duration were continuous and independent, we used a logistic regression (logit; Newton quasi test; Hosmer and Lemeshow 1989) to analyze the binomial distribution of injuries, mortality, occurrence of clonic and tonic seizures, and the proportion of fish stunned. In all statistical analysis, the level of significance set $\alpha = 0.05$.

TABLE 2.—Combinations of electric field strengths ($E = V_{rms}$/m) and current durations (one-phase, sinusoidal, 50-Hz AC) that stunned (+) or did not stun (−) Atlantic salmon; rms = root mean square, nd = not determined.

	Current duration (s)									
E	0.2	0.5	0.8	1	1.5	2	3	6	9	12
15	nd	nd	nd	nd	nd	nd	nd	−	−	−
25	nd	nd	nd	nd	nd	nd	−	+	+	+
50	nd	nd	nd	nd	nd	nd	+	+	+	+
75	nd	nd	nd	−	−	−	+	+	+	+
100	nd	nd	nd	−	+	+	+	+	+	+
125	nd	nd	nd	+	+	+	+	nd	nd	nd
150	nd	nd	nd	+	+	+	+	nd	nd	nd
175	nd	nd	−	+	+	+	+	nd	nd	nd
200	nd	nd	+	+	+	+	+	nd	nd	nd
225	nd	−	+	+	+	+	nd	nd	nd	nd
250	−	−	+	+	+	+	nd	nd	nd	nd

Results

Electrical stunning was shown to be very efficient in immobilizing fish. Injuries were not observed at electrical durations of less than 1.5 s at the threshold levels of field strength needed for stunning. The typical response after electrical stunning was an immediate epileptic-like seizure. The seizure was often vigorous and ceased gradually over the next minute. During electronarcosis, most fish were considered equivalent to stage 4 (Table 1). After a period of time, usually 2–4 min, depending on the electrical features, respiration slowly recovered and weak signs of reactivity occurred (stage 3). Within 10 min after stunning, most of the fish were in stage 1 or stage 2 and were often sensitive to tactile stimuli; however, their swimming activity was reduced and their equilibrium was affected (Table 1).

Epileptic-Like Seizures

The occurrence of a clonic phase was significantly dependent on the current duration and field strength (logit; $\chi^2 = 47.6$, df = 2, $P = 0.0000$). The clonic phase was usually induced when the electric duration was below 3 s, and in all cases the clonic phase shifted into a tonic phase. Mean duration of the epileptic-like seizure, including both the clonic and tonic phase, was 78 s (SE = ±25 s). Partial correlation analysis revealed no correlation between the duration of the epileptic-like seizure and field strength or current duration.

Electronarcosis

After the electrical stun, most individuals reached stage 4 or stage 3. A total of 16 fish died and these were categorized as stage 5. Electronarcosis could not be induced using current durations of 0.5 s or less, but at 0.8 s, electronarcosis was induced using field strengths above 200 V_{rms}/m (Table 2). Of the electric variables tested, current duration had the greatest influence. The minimum field strength that induced electronarcosis dropped from 200 V_{rms}/m at a 0.8-s duration to 25 V_{rms}/m for durations of 6–12 s (Table 2). Logit analysis of the results in Table 2 show that the proportion of fish stunned was significant, depending both on the field strength and current duration ($\chi^2 = 6.5$, df = 2, $P < 0.038$). Multiple regression of the results in Table 3 show that the duration of the unconscious condition, stages 3 and 4, was significantly dependent on the field strength, current duration, and fish length. All slopes were significantly positive (multiple regression; $r = 0.22$, df = 3.4, $P < 0.0005$), and the residuals were normally distributed.

Injuries

Some of the fish stunned by electricity had injuries that ranged from minor hemorrhages (observed as small blood clots) to severe injuries, including one or two fractures of the vertebrae. Hemorrhages were the most frequent injury observed (Table 4), and in some fish we observed ruptures in the secondary gill lamella. There was no evidence of external injuries to the fish, but temporary color changes in the dermis was observed; the fish became very pale on one or both sides and the anterior became light blue. In some fish we observed one or two dark stripes, indicating that the spinal column was probably injured.

Logit analysis of the results in Table 4 show that the frequency of injuries was significantly dependent on both the field strength and current duration ($\chi^2 = 32.3$, df = 2, $P < 0.0000001$), and current duration was the most important factor effecting

TABLE 3.—The proportion of Atlantic salmon stunned when exposed to various electrical field strengths ($E = V_{rms}/m$) and current durations (1–6 s) of, one-phase sinusoidal, 50-Hz AC. Also provided are mean durations of surgical anesthesia (stage 4) and deep narcosis (stage 3), as described in Table 1. The duration of unconsciousness is measured in seconds from the moment of electric exposure.

Current duration (s)	Field strength (*E*)	Sample size (*N*)	Fish length (cm)		Proportion stunned	Mean duration of unconsciousness (s)	
			Mean	SE		Surgical anesthesia	Deep narcosis
1	100	3	61.7	9.4	0.33	33	140
1	125	11	66.9	4.5	0.91	130	339
1	150	12	63.2	4.4	0.83	175	392
1	175	11	59.2	8.3	0.91	133	294
1	200	12	57.0	9.1	1.00	188	445
1.5	100	11	60.6	8.2	0.82	123	447
1.5	125	28	60.6	7.6	0.96	154	424
1.5	150	20	60.9	6.1	1.00	140	418
1.5	175	16	50.8	4.3	1.00	181	491
2	100	14	62.6	4.6	0.93	96	340
2	125	11	66.0	3.0	1.00	145	360
2	150	12	64.3	3.0	1.00	182	397
2	175	12	63.1	10.5	1.00	263	505
3	50	11	59.8	9.1	0.91	169	435
3	75	11	58.4	7.4	1.00	260	485
3	100	6	53.1	2.3	1.00	468	525
3	150	13	60.3	3.5	1.00	144	415
6	25	10	55.9	8.3	0.90	277	456
6	50	12	67.2	2.5	1.00	274	585

injuries. Durations less than 1.5 s did not result in injuries at the threshold field strength needed to stun (Table 4). At 2 s or longer, injuries occurred at all field strengths. Correlation analyses between the incidence of injuries and incidence of clonic seizures showed a significant negative correlation ($r = -0.3$, $N = 204$, $P < 0.00008$), suggesting that injuries were not probably due to epileptic-like seizures. Logit analysis on mortality failed to show a significant relation with field strength and current duration. The control group indicated that no injuries were caused by physical treatment (Table 4).

TABLE 4.—The proportion of broken vertebrae and hemorrhages in Atlantic salmon stunned by one-phase, sinusoidal, 50-Hz AC with variations in the electrical field strengths ($E = V_{rms}/m$) and current durations.

Current duration (s)	Field strength (*E*)	Sample size (*N*)	Proportion injured (SE)	
			Broken	Hemorrhage
1	100	2	0.00 (0.00)	0.00 (0.00)
1	125	11	0.00 (0.00)	0.00 (0.00)
1	150	10	0.10 (0.01)	0.30 (0.15)
1	175	10	0.20 (0.13)	0.20 (0.13)
1	200	11	0.46 (0.15)	0.73 (0.13)
1.5	100	10	0.00 (0.00)	0.00 (0.00)
1.5	125	27	0.00 (0.00)	0.00 (0.00)
1.5	150	20	0.00 (0.00)	0.05 (0.05)
1.5	175	10	0.09 (0.09)	0.27 (0.14)
2	100	11	0.27 (0.13)	0.27 (0.13)
2	125	10	0.10 (0.01)	0.40 (0.16)
2	150	10	0.40 (0.16)	0.70 (0.15)
2	175	11	0.27 (0.13)	0.46 (0.15)
3	50	7	0.14 (0.13)	0.14 (0.13)
3	75	10	0.20 (0.13)	0.40 (0.16)
3	100	3	0.00 (0.00)	0.67 (0.27)
3	150	11	0.31 (0.14)	0.72 (0.14)
6	25	10	0.40 (0.16)	0.50 (0.16)
6	50	10	0.20 (0.13)	0.70 (0.15)
Control group[a]		20	0.00	0.00

[a] The control group represents fish killed by percussion.

Discussion

Because injuries can be avoided using 50-Hz AC, electricity appears to be very effective for stunning market-sized Atlantic salmon before slaughter. Clonic seizures immediately after electrical stunning induced by short current durations were vigorous, involving high muscle activity. Sharber et al. (1994) suggested that injuries could be caused during the epileptic event that follows an electrical stimulus. According to this, one should expect a higher incidence of injuries when using electrical settings that cause clonic seizures. Our result on injuries (Table 4) give no such indication because the lowest proportion of injuries occurred at settings that produced the highest incidence of clonic seizures. What causes the seizure-like state in fish, and why current duration affects the type of seizure is not clear. In mammals and birds these seizures seem to be caused by the release of the neurotransmitters glutamate and aspartate (Meldrum 1975; Cook et al. 1992, 1996), but this has not been documented in fish

Previous research with use of PDC indicates that a stepwise increase of field strength increases the proportion of fish stunned and the duration of unconsciousness in channel catfish *Ictalurus punctatus* (Ellis 1975), Mozambique tilapia *Oreochromis mossambicus* (also known as *Tilapia mossambica*; Barham et al. 1989), and northern pike *Esox lucius* (Walker et al. 1994), which concurs with our findings. Furthermore, fish size has an important role in the sensitivity of fish to an electric field (Ellis 1975; Barham et al. 1987; Walker et al. 1994). We found that the proportion of fish stunned and the duration of unconsciousness were more affected by current duration than the other electrical variables tested. Hence, the field strength needed to stun Atlantic salmon is dependent on the current duration, especially in the first 3 s. The field strength needed to stun dropped from 200 V_{rms}/m at a 0.8-s duration to 50 V_{rms}/m at 3 s and stabilized at 25 V_{rms}/m at 6–12 s or more (Table 2).

Our behavioral studies on the stages of unconsciousness (Table 1), based on a modified protocol of Burka et al. (1997), indicate that electrically stunned fish are unconscious. Epilepsy is an indicator of unconsciousness in mammals (Cook et al. 1992) and poultry (Raj 1998). The lack of physical responses towards tactile and visual stimuli and the lack of opercular movement that we observed suggests that the central nervous system was not functioning correctly and that the fish were probably unconscious. However, these behavioral studies cannot be used to conclude definitely that the fish were unconscious, so further analysis using an electroencephalographic technique is required before such conclusions can be drawn.

Our finding that a stepwise increase of the field strength does increase the proportion of injured fish supports findings of Spencer (1967) and McMichael (1993). On the other hand, strong electric fields do not necessarily mean higher injury rates. Rather, the interaction between field strength and current duration primarily affects the proportion of injuries in stunned Atlantic salmon. All test groups in the experiments using current durations of 1.5 s or less and field strengths of 100–125 V_{rms}/m lacked evidence of an injury. Our findings on the relationship between injuries and current duration (Table 4) do not correspond with Spencer (1967) or Walker et al. (1994) who tested PDC and AC. This discrepancy raises uncertainty as to what role the current duration and field strength have on muscles that cause injuries in fish. If, as previously reported, the onset and degree of tetanus are dependent on current type (Lamarque 1990), frequency (McMichael 1993; Sharber et al. 1994) and field strength (Spencer 1967; McMichael 1993), then current duration should be less important. However, our results indicate that injuries are caused mainly by heavy muscle contractions during the electric exposure, not during the epileptic event afterwards. Furthermore, the time for muscle contractions to reach their maximum depends mainly on the electric field generated within the fish. Our experiment used seawater with a conductivity much higher than that of fish. So, it is likely that the law of impedance was in effect (i.e., the current immediately chooses the path around the fish, and it takes time for an electric field to become well-established within the fish). This might explain our finding that a reduction of current duration requires increased field strengths to stun (Tables 2, 3) and injure (Table 4) Atlantic salmon.

Use of electricity to stun fish before slaughter has the potential to improve the flesh quality by inhibiting the premortem struggle (Roth et al. 2002), which is known to cause external and internal damages (Robb 2001), an earlier resolution of rigor mortis, softer flesh texture (Nakayama et al. 1992; Roth et al. 2002), gaping (Dunajski 1979; Lavèty et al. 1988), and loss of shelf life (Lowe et al. 1993). In the commercial production of Atlantic salmon and trout, blood spotting accounts for 19% of the fish downgraded in secondary processing (Michie 2001). The types of injuries that can be produced by electrical stunning would probably cause downgrading in secondary processing. Before electrical stunning can be used on a commercial scale, more knowledge is needed on how different features of an electrical field, such as frequency, field strength and current duration, affect the central nervous system and muscles of different fish species. This will provide effective stunning of all individuals while avoiding injuries.

From the tests of one-phase, sinusoidal 50-Hz AC on Atlantic salmon, we conclude that electrical stunning has potential as a stunning method for fish before slaughter. By limiting the current duration and field strength to the thresholds values needed to stun Atlantic salmon, injuries can be avoided. Further, electrical stunning could be a more ethical initial step in slaughtering fish, as well as improving flesh quality.

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