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Electric stunning of trout: power reduction using a two-stage stun

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Abstract

Electrical stunning in water using a high frequency (1000 Hz) power source is a humane and practical method for killing trout, which results in damage free carcasses. However, the electrical power requirement can be high, particularly with high conductivity water. The equipment needed for the high frequency power supply significantly adds to the capital cost of the equipment and can make such equipment impractical, particularly for use in high conductivity water. A two-stage approach to stunning has been demonstrated which reduces the electrical power required by over 80%. The approach is based on the observation that the electric field strength needed to induce rapid insensibility is greater than the electric field strength required to maintain stunned fish in a state of insensibility until they are beyond the point of recovery. It is further proposed that since the electric field required for the prolonged second stage is quite low, it might be possible to use a 50 Hz power source without causing carcass damage.

Keywords: Welfare; Trout; Slaughter; Electric stunning; Power requirement

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1. Introduction

There is a need for a new harvesting system for portion-sized rainbow trout in the UK. Normal practice in the UK and elsewhere has been to kill trout by asphyxiation in ice slurry. This process is cheap to implement, can be achieved at high rates and results in high quality carcasses. It is however considered to compromise fish welfare because it results in a long period of stress before the fish becomes insensible (FAWC, 1996; Southgate and Wall, 2001). In response to this situation, Robb and Kestin (2002) reviewed a wide range of alternative fish killing methods and evaluated their impact on fish welfare. They concluded that no available slaughter method met the needs of the UK trout industry for fish welfare standards, carcass quality and processing speed; however, they identified electric stunning as an approach with potential to meet these needs, given suitable development.

Subsequent research investigated the electric field strengths and exposure durations required to generate permanent insensibility in trout (Robb et al., 2002); showed that blood spotting, haemorrhaging and bone breakage could be reduced or eliminated by the use of a high frequency (1000 Hz) electric field (Lines et al., 2001); investigated the relationship between required electric field strength and water conductivity (Lines and Kestin, 2004); and built and tested a transportable rotary device for humane trout slaughter (Lines et al., 2003). On farm assessment of this rotary device confirmed that high standards of carcass quality and fish welfare could be achieved but suggested that commercial equipment would benefit from having a higher throughput, and that a simpler approach using fixed equipment with no moving parts would be more suitable for many situations.

An alternative to the rotary device is a system comprising a single stationary tube through which the fish are pumped (Lines et al., 2003). Electrodes line the pipe walls so that fish flowing through the pipe are exposed to an electric field for the full transit duration and exit the tube stunned beyond the point of recovery. This configuration requires no moving parts and has the potential to facilitate harvest at very high speeds. However, the water flow must be sufficiently fast to ensure a uniform flow of fish through the tube. This results in the need for a long tube containing a large volume of water and consequently has a very high electric power requirement. The power required to generate an electric field in water is proportional to the water volume, the water conductivity and to the square of the electric field strength. A typical commercial arrangement might comprise a 200 mm square tube, 30 m long with fish flowing through the pipe at 0.5 m/s. In water with a conductivity of 500 μS/cm an electric field of about 2.5 V/cm would be required to produce permanent insensibility in the fish (Lines et al., 2003), which would result in a power demand of over 3 kW. This is of concern, not because of the cost of power, but because of the capital cost of the electronic unit required to generate and control the 1000 Hz voltage signal at this power. The approach is not suitable for use in sea water since the very high water conductivity would result in a power demand of over 100 kW. It is therefore of both immediate and longer term interest to identify power reduction strategies.

Lambooij et al. (2002) have reported an approach to stunning eels, which uses a short exposure to a high electric field followed by an extended exposure to a lower electric field. It appears that the process of electric stunning may be considered to comprise two parts. Exposure to an electric field is required initially to generate insensibility in the fish. This has been termed the stun initiation. After this, a second insult is required to prevent the recovery of sensibility. This has been termed the stun maintenance. It appears that if insensibility is maintained for a suitable length of time then the recovery becomes impossible for the fish. Death may then occur without further intervention or as a result of bleeding or deliberate asphyxiation. The work described in this paper uses exposure to electric fields for both the stun initiation and stun maintenance. It explores some of the requirements for each of these processes and demonstrates how this approach can result in large reductions in electrical power demand. It is possible that other approaches could be used to maintain insensibility such as immersion in ice slurry or CO_2 enriched water. These have not been investigated.

The experimental work has been limited to water of 500 μS/cm conductivity; however, we expect that the electric fields can be adjusted for fresh water with a wide range of conductivities following the approach described previously (Lines and Kestin, 2004).

The experimental work reported in this paper was done in accordance with the UK laws relating to experimentation on animals and the experiments were designed to minimise suffering. No fish were used in experiments more than once and all fish that showed signs of recovery from the stun were quickly killed either by a blow to the head or by exposure to an electric field known to be lethal.

2. General description of experimental work

The fish used in this experiment were commercially farmed rainbow trout, which had reached harvest size. They had a mean mass of 384 g and individual fish had a standard deviation around this mean of 60 g. The trout were housed in a concrete raceway in farm water of conductivity 500 μS/cm, prior to slaughter. The experiments all took place in farm water. The stunning tank had a rectangular cross section, 40 cm long and 15 cm wide, and a water depth of 15 cm. Sheet electrodes covered the two largest sides of the tank.

The trout were removed from the concrete raceway using a net, and transferred to the stunning tank in groups of five. They were orientated parallel to the electrodes by the restricted width of the tank. A few seconds after placing the fish in the slaughter tank, an electric field was applied across the electrodes to stun the fish. The fish were then transferred to a well-oxygenated observation tank where they were monitored for 5 min for behaviour indicating the recovery of sensibility.

Behavioural indicators of insensibility have been investigated by Kestin et al. (2002) and by Robb and Roth (2003). Observations of brain function using visually evoked responses (VER) have shown that the return of normal brain function following an electric stun is well correlated with the return of normal periodic motion of the gill covers and the eye roll reflex. These simple behavioural tests have been used to determine the state of sensibility of the experimental fish in this work. This approach has been used previously by Roth et al. (2003) and Robb et al. (2002).

Fish that recovered to the point where they exhibited periodic motion of the gill covers were deemed to have recovered sensibility. They were killed by a blow to the head. Those that failed to recover regular opercular movement within 5 min were deemed to be permanently insensible. Where there was doubt about the opercular movement, fish were removed from the water and examined for eye roll.

3. Exposure duration and electric field required to initiate insensibility

The purpose of the first trial was to examine the relationship between exposure duration and the duration of the resulting period of insensibility for one electric field strength and water conductivity.

Groups of five fish were stunned using an electric field strength of 2.5 V/cm and exposure durations of 2, 5, 10, 20, 30 and 60 s. Each condition was replicated four times (20 fish per condition) and observations were made of the time required by the fish to recover signs of sensibility.

The means and standard deviations of the periods of insensibility following removal of the electric field were 24 ± 16, 47 ± 16, 61 ± 20, 98 ± 20 and 180 ± 42 s for 2, 5, 10, 20 and 30 s exposures, respectively. No fish recovered after exposure to the electric field for 60 s. Data points for individual fish are shown in Fig. 1. Only one fish remained insensible for less than 1 s following removal of the electric field. This occurred following a 2 s exposure. This fish was either not stunned, or very quickly recovered sensibility. These results show that the average period of insensibility increases with the duration of exposure to the electric field and that there is considerable variation in individual recovery times. These suggest that sustained insensibility under these conditions is generated in less than 5 s and for most fish in less than 2 s.

All the fish exposed to the electric field for 10 s or less recovered sufficiently to exhibit periodic opercular motion within 5 min. Following the 20 s exposure, 9 of the 20 fish (45%) did not recover periodic opercular motion within 5 min. These were classified as permanently insensible. Following a 30 s exposure to the electric field 90% of the fish were classified as permanently insensible, and following the 60 s exposure all 20 fish were classified as permanently insensible.

Trout were also exposed to a 1000 Hz electric field of 1 V/cm for durations of 2 and 5 s. Immediately after the 2 s exposure all 10 of the trout tested, exhibited vigorous aversive behaviour, suggesting that they had not been stunned. After the 5 s exposure, 4 of the 10

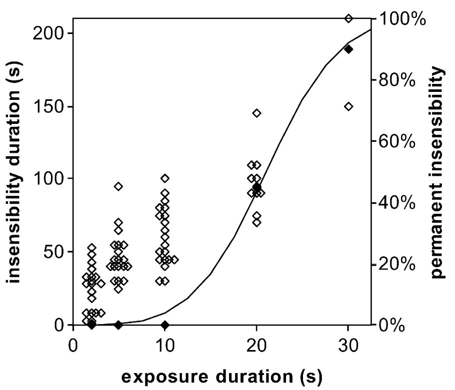

Fig. 1. Observed relationship between duration of exposure to a 1000 Hz electric field of strength 2.5 V/cm in water of conductivity 500 μS/cm and resulting insensibility durations (open markers). Also shown is the proportion of the fish that become permanently insensible (solid markers) and a best fit normal distribution line to these data (mean, 21 s; standard deviation, 6.3 s).

test fish showed immediate aversive behaviour. The study was terminated at this point. We concluded from this that that an electric field of 1 V/cm under these conditions is insufficient to generate sustained insensibility within 5 s.

4. Exposure duration and electric field required to maintain insensibility until the fish are beyond the point of recovery

Trout were stunned by exposing them for 2 s to a 1000 Hz electric field of 2.5 V/cm. The electric field was then reduced to 1.0, 0.5 or 0.25 V/cm for 58 s. At the end of this period all the fish exposed to the 1.0 or 0.5 V/cm stun maintenance fields remained insensible for some time (20 fish per condition). Only one group of five fish was exposed to the 0.25 V/cm since some of these recovered sensibility and started to move vigorously even while exposed to the electric field. We concluded from this, that electric fields of 1 and 0.5 V/cm were sufficient to maintain insensibility but that an electric field of 0.25 V/cm was not sufficient.

Having established that a 1 V/cm electric field was insufficient to initiate rapid insensibility but sufficient to maintain insensibility we made a comparison between a two-stage stun using 2.5 and then 1 V/cm and single-stage stuns using field strengths of 1.3, 1.8 and 2.3 V/cm. The results given in Table 1 show the proportion of fish in each group, which were stunned beyond the point of recovery (this is, for convenience, termed mortality). Also shown in the table is the calculated electrical energy per litre of water, which is required to sustain the electric field for the required time. Comparison of the first two lines of the table shows that the two-stage stun has a lower energy requirement than the single-stage stun, and that it results in a significantly higher mortality. The difference in these two mortalities is significant at $p < 0.005$.

Table 2 shows the effect of increasing the stun initiation exposures from 2 to 4 and 8 s, using stun maintenance fields of 0.5 and 1 V/cm to give a total exposure duration (initiation plus maintenance) of 60 s, and of using a stun maintenance field of 1 V/cm to give a total exposure duration of 30 s. These results indicate an increase in mortality as exposure to the stun initiation electric field increases and an increase in mortality as the maintenance field increases. At each stun initiation duration, each total exposure duration, and each maintenance electric field, 100% mortality is achieved using between 32 and 36 J/l

Table 1
Comparison between a two-stage stun and single-stage stuns

Stun initiation		Stun maintenance		Mortality (%)	Number of fish	Energy (J/l)
Duration (s)	Electric field (V/cm)	Duration (s)	Electric field (V/cm)			
2	2.5	28	1	90	20	20
30	1.3	–	–	45	20	27
30	1.8	–	–	85	20	50
30	2.3	–	–	90	20	81

The term mortality is used to signify the proportion of fish stunned beyond the point of recovery. The electrical energy requirement per litre of water is calculated. Data on the first line of this table is also presented in Table 2.

Table 2
Mortality and energy requirement resulting from exposure to 2, 4 and 8 s stun initiation field of 2.5 V/cm, 1000 Hz, followed by 1000 Hz stun maintenance fields of 0.5 or 1 V/cm, for a total exposure duration (initiation plus maintenance) of 30 or 60 s

Stun initiation duration (s)	Total stun duration 30 s, maintenance field 1 V/cm			Total stun duration 60 s, maintenance field 0.5 V/cm			Total stun duration 60 s, maintenance field 1 V/cm		
	Mortality (%)	Number of fish	Energy (J/l)	Mortality (%)	Number of fish	Energy (J/l)	Mortality (%)	Number of fish	Energy (J/l)
2	90	20	20	75	20	14	100	20	35
4	95	20	26	95	20	20	100	20	41
8	100	20	36	100	20	32	100	20	51

electrical power. This can be compared with previous work (Lines and Kestin, 2004) using a single-stage stun, which recommended electric fields of 2.9 and 2.3 V/cm for 30 and 60 s exposures and so had energy requirements of 126 and 159 J/l, respectively. From Table 2 we draw the tentative conclusion that while differences in the parameters of a two-stage stun may result in different energy requirements to achieve 100% mortality, these are relatively small compared to the difference between the energy requirements of a single- and two-stage stunning process.

Up to this point, a 1000 Hz electric field has been used in order to avoid the haemorrhages and other carcass damage, which have been associated with a 50 Hz electric field. The generation of a 1000 Hz electric field is considerably more complex than that of a 50 Hz field since the latter can be derived directly from the mains electric supply. Since it seemed possible that the low electric field strengths used in the stun maintenance period might be too small to damage the carcass, comparisons were made using a 1000 Hz and a 50 Hz maintenance field. A short pause was also introduced between exposure to the stun initiation and the stun maintenance electric fields. The purpose of this was to mimic the situation in a stunning tube where the electric fields running at two different frequencies would have to be separated by a small distance to avoid interference between the fields. The results of these tests are given in Table 3. In each condition the stun initiation was provided by a 2 s exposure to a 1000 Hz electric field of 2.5 V/cm. These results indicate that a 50 Hz maintenance field generated a slightly higher mortality than a 1000 Hz field, but that the introduction of a pause reduced the mortality level again to that achieved by a 1000 Hz field. The electrical energy required at 1000 Hz is, however, significantly reduced with

Table 3
Comparison of the effect of 1000 and 50 Hz stun maintenance electric fields

Stun maintenance frequency (Hz)	Total duration 30 s, maintenance field 1 V/cm			Total duration 60 s, maintenance field 0.5 V/cm			Total duration 60 s, maintenance field 1 V/cm		
	Mortality (%)	Number of fish	Energy (J/l)	Mortality (%)	Number of fish	Energy (J/l)	Mortality (%)	Number of fish	Energy (J/l)
1000	90	20	20	66	35	14	90	40	35
50	90	20	20 (6)	100	20	14 (6)	100	30	35 (6)
50 after 2 s pause	90	20	20 (6)	75	20	14 (6)	100	20	35 (6)

The electrical power required at 1000 Hz is shown in parentheses where this differs from the total power requirement. The first line in this table represents the same data set as given in Table 2.

100% mortality being achieved using only 6 J/l. This is less than 5% of the requirement previously identified.

The experiments also included exposure to a maintenance field of 0.5 s with a total exposure of only 30 s. These results are not shown in Table 3. Only five fish were used for each of the three conditions and resulted in mortality of 0, 60 and 60% for the 1000, 50 and 50 Hz after a 2 s pause, respectively. The low mortality indicated that this was unlikely to be a useful area to explore so the trial was terminated early.

5. Carcass quality

The most significant carcass quality problem associated with electric stunning is the incidence of haemorrhaging. The incidence of haemorrhaging following a two-stage stun was, therefore, investigated and compared with that following asphyxiation and two other approaches to electric stunning. One hundred trout were killed by each method and the carcases were filleted for inspection. The fillets were graded using a four point ordinal scale, which was developed in collaboration with trout retailers (Lines et al., 2001). This scale identifies four levels of carcass haemorrhaging:

L0: no detectable haemorrhage;
L1: very minor haemorrhaging, not likely to lead to downgrading;
L2: moderate haemorrhaging, likely to lead to some downgrading;
L3: haemorrhaging that would lead to downgrading.

Trout were killed using the following four methods:

- Asphyxiation. This was to imitate current industry practice.
- A single-stage electric stun using a 60 s exposure to a 2.5 V/cm, 1000 Hz electric field.
- A two-stage electric stun comprising 2 s exposure to a 2.5 V/cm, 1000 Hz stun initiation field followed immediately by 58 s exposure to a 1 V/cm, 50 Hz stun maintenance field. This is the proposed two-stage stun method.
- A two-stage 50 Hz electric stun comprising a 2 s exposure to a 2.5 V/cm, 50 Hz stun initiation field followed immediately by a 58 s exposure to a 1 V/cm, 50 Hz stun maintenance field. This approach is simpler and cheaper to implement than using 1000 Hz but was considered likely to cause carcass damage.

Levels of carcass damage with all the slaughter methods were low so the differences shown in Table 4 are only of low statistical significance. The data is on an ordinal scale and so has been analysed using a model based on cumulative probabilities following McCullagh and Nelder (1989). This approach fits the data to an arbitrary distribution and assigns to each treatment a parameter together with a standard error for this parameter. The modelled damage scores resulting from this fitting process are shown in Table 5. Inspection suggests these to be a reasonable interpretation of the data in Table 4. Also shown in Table 5 for each treatment is the model parameter generated in the fitting process together with the standard error of this parameter. These parameters suggest that the lowest level of damage

Table 4
Fillet damage associated with four slaughter methods

	Fillet damage level			
	L0	L1	L2	L3
Asphyxiation	90	5	4	1
Single-stage stun 60s, 2.5 V/cm, 1000 Hz	92	4	2	2
Two-stage stun using 1000 and 50 Hz	89	4	5	2
Two-stage stun using 50 Hz	85	5	5	5

100 trout were used for each method. Fillet damage is graded from L0 (no detectable haemorrhage) to L3 (haemorrhaging that would lead to downgrading (see text).

Table 5
Fitted values from statistical model

	Fillet damage level				Model parameter	S.E. of parameter
	L0	L1	L2	L3		
Asphyxiation	90.1	4.1	3.6	2.2	0	
Single-stage stun 60 s, 2.5 V/cm, 1000 Hz	92.0	3.4	2.8	1.8	−0.23	0.33
Two-stage stun using 1000 and 50 Hz	89.0	4.5	4.0	2.5	0.12	0.31
Two-stage stun using 50 Hz	84.7	6.1	5.6	3.6	0.50	0.30

is associated with the single-stage stun, followed by asphyxiation and the two-stage stun using 1000 and 50 Hz, while the highest level of damage is associated with the stun using only 50 Hz. The differences between the model parameters for the first three treatments are less than the standard error while the model parameter for the 50 Hz stun, exceeds that of asphyxiation by more than 150% of the standard error. From this we may draw an expectation, at low statistical significance, that there is little difference in the damage caused by the first three approaches to trout slaughter but that the option of stunning using only 50 Hz mains will be associated with higher levels of damage even when used as part of a two-stage stun.

6. Conclusion

The results presented in this paper show that trout can be electrically stunned in water beyond the point of recovery using a two-stage approach, and that this approach requires very much less electrical power than a single-stage stun. This reduction in power is achieved by separating the electric field requirement for generating a state of insensibility in the trout from the much lower electrical field strength required to maintain the state of insensibility until the fish are beyond the point of recovery. A further reduction in the requirement for high frequency electrical power (1000 Hz) can also be made since the lower strength electrical field used to maintain the state of insensibility can be implemented using 50 Hz (mains) frequency without, it appears, causing carcass damage.

The approach enables 100% mortality in portion sized trout to be achieved in water of conductivity 500 μS/cm using as little as 14 J of electrical power per litre of water, of which only 6 J/l needs to be generated at 1000 Hz. This contrasts with the requirements for a single-stage stun, which requires over 120 J/l, all generated at 1000 Hz. This power reduction should significantly reduce the capital cost of commercial trout harvesting equipment. It is also a first step towards a practical electrical stunning approach in sea water.

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