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Electrical stunning of edible crabs (Cancer pagurus): from single experiments to commercial practice

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Abstract

*To determine the optimal electrical stunning conditions for edible crabs (*Cancer pagurus*) their impedance was investigated along with currents with the potential to render the animal insensible within 1 s. This information was used to develop a commercial stunner and determine conditions that both stun and kill the animals instantaneously. Results show that the crabs' impedance is dependent on the current frequency with the optimum outcome seen at net frequencies of 50–60 Hz. The proportion of animals stunned was dependent on the potential difference with 220 V required to stun an animal unconscious within 1 s. Any attempts to kill the crab with asphyxia after a 10-s exposure to electricity failed as 30% of crabs recovered within an hour. A thermal shock, pre- or post-stunning prevented this recovery. Autotomy was not avoided and approximately 4–7% of crabs lost one or more appendage. Electricity caused localised over-heating, but a current of 10-s duration did not cause heating of the carapace. We conclude that electrical stunning used in combination with a thermal shock may stun and kill the animal instantaneously.*

Keywords: *animal welfare, crab, crustacean, electricity, slaughter, stunning*

Introduction

Unlike invertebrates, the welfare of poultry and mammals as regards slaughter procedure is regulated in most European countries following recommendations from the EU (EFSA 2004). Similar recommendations also apply for farmed fish (EFSA 2004) while, for decapods, the welfare is only regulated for scientific purposes (EFSA 2005). A number of countries, including Norway, have integrated the welfare of decapods and cephalopods into the same laws as vertebrates (Anon 2009), as they are animals considered to learn from their experiences. To the authors' knowledge there are yet to be any laws or regulations protecting the welfare of decapods during slaughter, put into action.

Decapods, such as the edible crab (*Cancer pagurus*), tend to be processed in one of two ways; they are either killed using freshwater (Edwards 1979) — which is both time-consuming and space intensive — or are processed in a live state. Since processing of live crabs often entails carving without destruction of ganglia, the potential exists for crabs to experience an unpleasant sensation over a considerable period of time. Similarly, with crabs inserted live into boiling water, up to 2 min are needed before the internal temperature reaches the range where responses are lost (Roth & Øines 2010). This treatment provokes an ethical debate. Recent studies, both on hermit (*Pagurus bernhardus*) (Elwood & Appel 2009) and shore crabs (*Carcinus maenas*) (Magee & Elwood 2013) suggest that decapods have the ability to experience, learn and avoid a painful stimulus. Therefore, the concept of stunning decapods instantaneously into an irreversible insensible state prior to processing may be an important step towards improving welfare.

Previous studies into the stunning and killing of edible crabs have shown that any attempt to kill or stun the crabs using gas or a thermal shock requires time before the crabs can be considered unconscious (Baker 1955; Roth & Øines 2010). From that perspective the use of electricity is a promising stunning method, since the animals can be stunned almost instantaneously (Baker *et al* 1975; Baker & Dolan 1975; Robb 1999; Ogawa *et al* 2007; Roth & Øines 2010). The stunning efficiency is dependent, initially, on the amperage flow through the crab, caused by the potential difference across it and then the current duration (Baker *et al* 1975; Robb 1999; Roth & Øines 2010). In seawater, edible crabs can be stunned unconscious within 1 s using electric field strengths equivalent to 550 V m^{-1} (Roth & Øines 2010). Lower field strength would fail to stun the animal within 1 s and cause massive autotomy (Roth & Øines 2010). Increasing the current duration would eventually stun the animal, prolonging the insensible condition and inhibit autotomy (Roth & Øines 2010). Any attempts to electrocute and kill the animals have so far failed, suggesting that electricity can only be used to stun the animal unconscious (Baker *et al* 1975; Robb 1999; Roth & Øines 2010). In fish, it is known that thermal insult following an electrical stun can prevent recovery (Lambooij *et al* 2008, 2013) and the same may apply for decapods.

Figure 1

The Stansas#01™ Electro-stunner (Seaside A/S, Stranda Norway). The crabs or fish are transported through the stunner with a conveyer belt acting as one electrode, while the other electrodes take the form of dangling spoons, which crabs come into contact with.

However, the challenge of stunning the crabs on a large scale remains. Stunning them in seawater requires much energy, but recent developments in fish have shown that dry stunning is an appropriate technique for several species (Lamboiij *et al* 2010; Erikson *et al* 2012). In fish, dry stunners work with the conveyer belt acting as one electrode through a series of hanging metal plates which act as the other (Figure 1). The same principal could, perhaps, also be applied in crabs.

The aim of this study, therefore, was to develop stunning and killing protocols for edible crabs using electrical dry stunners and disseminate this knowledge into commercial practice.

Materials and methods

In order to develop a commercial stunner for edible crabs with the capacity equivalent to several tons per h, the project was divided into three main phases. Phase 1 investigated the electrical characteristics of crabs, such as impedance and phase angle. This was done in order to determine the current frequency at which the crabs experienced the lowest resistance. Phase 2 sought to determine the electrical setting required to stun the animal within 1 s and the duration required to prolong an insensible state until death. While Phase 3 aimed to develop a commercial stunner to be tested under semi- and full-scale production. Phase 1 was carried out at Heløysund, Rogaland, Norway, while all other experiments along with phases 2 and 3 were carried out at Hitramat AS, Sør Trøndelag, Norway.

Phase 1 — Impedance related to frequency

The experiment was conducted by taking one crab at a time and placing it into a tank filled with seawater to kill it with an overdose of Metacain (Finquel Vet, ScannVacc, Norway). This was done to ensure that the crab was completely stationary during measurements of impedance. When all responses were lost, the crab was placed, immediately, onto a plate of stainless steel acting as one electrode, while the other plate electrode was placed on top of the carapace, anterior to the eyes. This was done to simulate the commercial conditions in which crabs are stunned electrically via the Stansas#01™, (Seaside A/S, Stranda, Norway) (Figure 1). The electrodes were then connected with coaxial cables to the high and low connection terminals on an Agilent 4294A Precision Impedance Analyzer (Agilent Technologies Inc, USA). All impedance and phase angle measurements were taken without changing the position of the crab. The impedance analyser was programmed to scan over a logarithmic-distributed frequency range from 40 Hz to 1 MHz and took measurements of impedance and phase angle at 43 frequencies at both 0.5 V and 20 mA. To reduce the influence of noise, the impedance analyser was programmed to deliver an average value for each measured frequency, such that the value of each of the 43 measured frequencies for each crab represented an average of 256 measurements. To determine the importance of position, one crab was put into standing position by placing a small piece of polystyrene beneath it.

Impedance related to voltage

To assess the changing characteristics of impedance related to voltage, after impedance and phase angle measurement, crabs were exposed, individually, to 50 Hz sinusoidal AC current at approximately 110 and 220 V root mean square (RMS). Measurements of RMS values for ampere were carried out using ampere nippers connected to the oscilloscope and pinched on the wiring between the transformer and the positive electrode. Results were recorded using a laptop which linked with a 20 MHz, FLUKE 123™ industrial scope-meter (Fluke Inc, Everett, WA, USA) via a USB connection. For ampere measurements at 110 and 220 V, a FLUKE 80i-110s AC/DC current probe (Fluke Inc, Everett WA, USA) was used together with a scope-meter. On the PC, FlukeView scope-meter software for Windows SW90W (BV Tilburg, The Netherlands) was used to read the signal. Impedance values for 50 V AC and 50 Hz were calculated from the recorded values of RMS voltage and ampere.

Phase 2 — Stunning of edible crabs

To determine the electrical parameters required for stunning live crabs, one crab was placed at a time in between the electrodes and exposed to 110–220 V, 50 Hz AC for 1, 5 and 10 s. After stunning, behavioural responses were recorded in accordance with Roth and Øines (2010) to determine each crab's level of consciousness. Behavioural responses focused on the appendages/chelipeds, mouth (from the posterior ganglion), antennules and eyes (from the anterior ganglion). These behavioural responses were then summarised in order to ascertain responsiveness on a scale from 0–8 (Table 1). To assess death, crabs were placed back into ambient seawater after stunning and if no signs of recovery were observed within the next 60 min the animal was classed as dead.

Table 1 Protocol for scoring the conscious condition of edible crabs (*Cancer pagurus*), adapted from Roth and Øines (2010).

		Behaviour score		
		Normal response (2)	**Weak response (1)**	**No response (0)**
Anterior ganglion	Eyes	Eyes respond to visual stimuli lowering into sockets in the carapace. The eye re-emerges back out	The eyes remain hidden in the sockets, but responses can be seen with touching	The eyes show no response to any given stimuli and fall out of sockets when the crab is turned upside down
	Antennule (plural antennules)	Vigorously coming out to smell and taste the new environment and protects antennules by folding into sockets on tactile stimuli	Often withdrawn into the sockets. When lifted out antennules are slowly drawn back into sockets	Antennules remain out after they are lifted from their sockets
Posterior ganglion	Appendages	Actively trying to escape and protect itself while touching the apron	Weak response or complete failure to walk or protect itself. With no general response claws on the cheliped cannot be forced open	No response. The claws can be forced open without resistance
	Mandibulares/maxillipeds	Normal response and resists opening	Weak response. The maxillare can be opened, but fall back into a closed position	No response. Mandibulares remain open when forced

Behavioural score is given on the responsiveness (0–2) of the 1) eyes, antennules and 2) appendages and mouth representing the 1) anterior and 2) posterior ganglion. Summarising the behavioural score will quantify the crabs' conscious condition on a scale from 0 to 8.

Phase 3 — Commercial stunning of edible crabs

Originally, the process line for edible crabs included several steps. The first involved live chilling the crabs using –1°C seawater for 30 min. The idea being to ensure the crab was lying still during scanning for meat content using a QVision, NiR scanner (QVision A/S, Norway), which it did not. Thereafter, crabs were placed into 800-L tanks containing freshwater to ensure killing prior to boiling. This was done to prevent autotomy during boiling.

For electrical stunning of edible crabs a STANSAS #01 (Figure 1) was rebuilt and adjusted to cater for edible crabs. This included an isolated ring transformer providing 0–220 V, 50 HZ AC. Several series of 1-cm wide electrodes were installed above the conveyer belt, providing a mesh of electrodes remaining in constant contact with the crab. At the entrance of the electro-stunner, a plastic plate was installed, pressing the crabs down onto the conveyer belt to enhance contact. Additionally, saltwater was sprayed over the crabs to reduce contact resistance. For electrical stunning all crabs were exposed to 220 V for 10 s.

For the commercial trials, the electro-stunner was installed after the live-chilling tank to overcome the problem of crabs moving during scanning. For commercial stunning three scenarios were considered: i) crabs are live-chilled, electrically stunned and placed in purely freshwater (current method); ii) crabs are live-chilled, electrically stunned and stored dry in air; and iii) crabs are electrically stunned and placed into tanks containing ice slurry.

Commercial testing began by evaluating the stunning efficiency of the electro-stunner. Four batches of either live-chilled crabs (n = 2) or crabs maintained at ambient temperature (n = 2) were placed in the electro-stunner and behaviour assessed on exiting it. A total of 200 live-chilled crabs and 200 maintained at ambient temperature were evaluated.

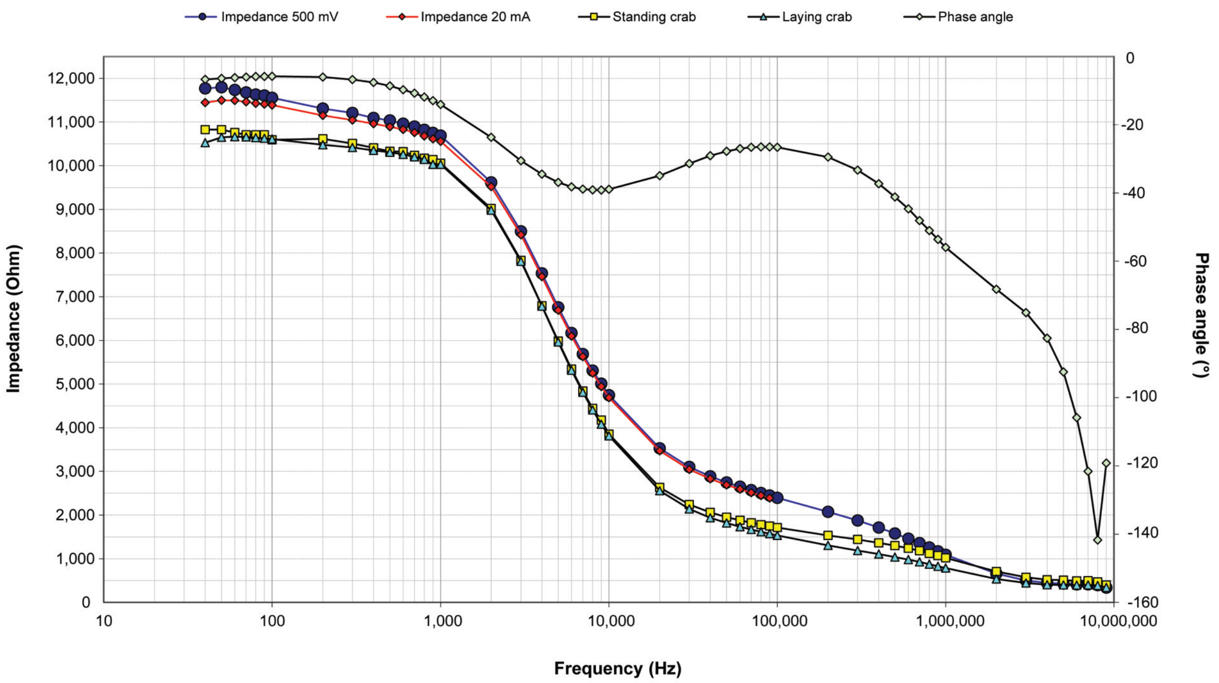
For evaluating the method of stunning in conjunction with killing, 30 live-chilled crabs, maintained at ambient temperature, were electrically stunned, evaluated and placed into polystyrene boxes containing ice slurry. The crabs were then tracked for the following hour: evaluated every 5 min for the first 15 min and, thereafter, at 10-min intervals. In the commercial production, live-chilled crabs, having been electrically stunned, were placed into either ice slurry or dry ice and then evaluated after 30 and 60 min.

To evaluate the proportion of autotomy, both live-chilled crabs (n = 115) and crabs held at ambient temperature (n = 109) were sent through the electrical stunner. The number of lost appendages/chelipeds were counted on exit.

IR measurements

To evaluate the effect of heating, a ThermaCam® IR video camera (Flir systems Inc, Wilsonville, Oregon, USA) was placed at the end of the electro-stunner to measure the heat signature of the crabs after electrical stunning. A controlled experiment was carried out by exposing the crabs to 0–60 s of electricity and measuring the heat increase both at the point of contact with the electrodes and on the carapace in general. A series of experiments (n = 5) were carried out, where crabs were exposed to 10 s of electricity and the heat signature followed over the next 3 min and compared against a control group, not exposed to electricity.

Figure 2



Average impedance (Ohm) (left axis) and phase angle (degrees) (right axis) of edible crabs (*Cancer pagurus*) exposed to a constant 500 mV or 20 mA at 40–10 MHz. Also presented is the impedance between an edible crab exposed either standing on its appendages versus laying on a steel plate.

Ethics

These experiments on electrical stunning of edible crabs were carried out in collaboration with the Norwegian food authorities. All researchers are in possession of FELASA certification for live experimentation of animals.

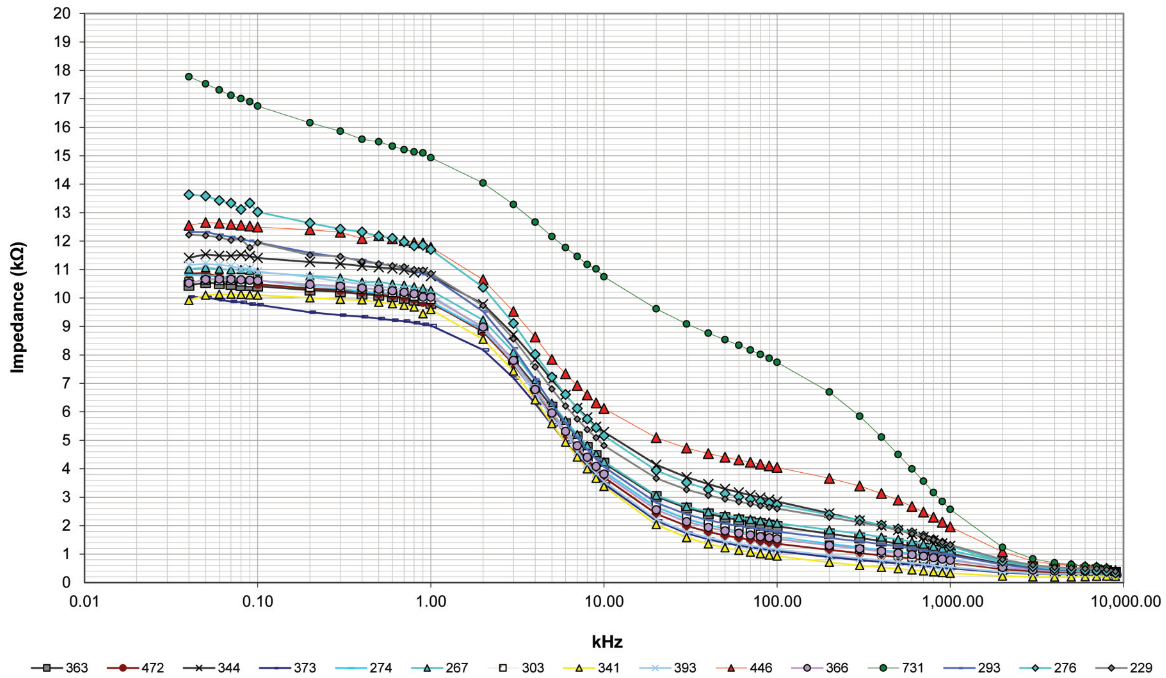
Statistical analysis

To test the continuous and dependent variables, impedance and phase angle, against the independent and continuous variable, electrical frequency, linear regression was used. Correlation analysis sought to verify the relationship between the size of the crab, impedance and amperage flow. For testing the proportion of crabs stunned or undergoing autotomy against continuous and independent variables, such as voltage and current duration, logistic regression was used as the statistical model (Walds Chi-square). The behavioural score was added as codes and counts into the logistic regression model. To test for differences in the probability of autotomy, a *Z*-test was used. A Repeated Measures ANOVA was used to test the post-stun temperature difference between crabs immediately exposed to 10 s of electricity or to 3 min.

Results and Discussion

The electrical properties of biological tissue thighly dependent upon the applied voltage across the tissue (Šel *et al* 2005) and at higher voltage the impedance will decrease. However, the biological tissues permittivity (ε) and conductivity (σ) makes the biological impedance frequency dependent (Schwan 1963, 1984). Although crabs do have an exoskeleton, their electrical properties show similarities with vertebrates with dispersion zones (Schwan 1963, 1984, 1994; Grimnes & Martinsen 2008) and the crab changing electrical characteristics along with frequency (Figure 2). In addition to the dispersion zones, the crabs have a rather unusual phase characteristic whereby the phase angle drops below –90° at high frequencies. This indicates a possible transfer function of higher order, a phenomenon caused by the influence of the exoskeleton and the contact capacitance to the crabs' internal biological tissue. The impedance spectrum, both voltages and ampere measured, across biological tissue are frequency-dependent with dispersion characteristics (Schwan 1963, 1984), which was also observed for crabs (Figure 2). This effect is shown on the impedance (Ω), which is dependent on the current frequency ($P < 0.0005$; linear regression), with maximum impedance in the region of 50 Hz. This clearly shows that the optimum stunning frequencies for crustaceans is within net frequencies, where cheap AC technology can be used (Figure 2). This is because, according to models for bioimpedance (Grimnes & Martinsen 2008), at maximum impedance the voltage differences over the cell membranes are expected to be at their highest. At 50 Hz, there was an individual variation in impedance ranging 10.1 to 15.5 kΩ (Figure 3). This was dependent on the weight of the crab ($P < 0.05$; $r = 0.64$), but not the size of the carapace ($P > 0.22$), indicating that it is the volume of the crab that is of importance. Whether the crab is standing on its appendages during stunning or not is of little relevance as compared to individual differences (Figure 2).

Figure 3



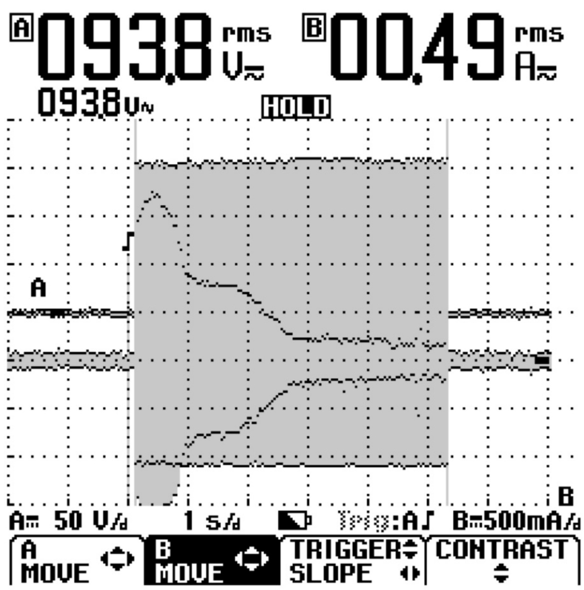
Impedance of each single edible crab (*Cancer pagurus*) as a function of weight.

As experienced by Robb (1999), the amperage flow during the first second of stunning using 220 V AC varied considerably from 0.65–2.2 amps between each crab. This is likely due to the low conductivity of the carapace and the fact that crabs have high internal salinity acting as a capacitor. This effect is demonstrated in Figure 4, where the amperage flow was variable against time, increasing rapidly the first 0.5 s before gradually decreasing over the next 5 s as the contact resistance increased with heating. Previous studies on fish have shown that 0.5 s is the time limit for stunning (Lambooij *et al* 2010), which may be due to contact capacitance (Zivotofsky & Strous 2012).

Phase 2 stunning

As shown in Table 2, there were significant differences in the behavioural scores between crabs stunned at 110 and 220 V, decreasing with the current duration ($P < 0.05$; logistic regression). The difference in score between 110 and 220 V was due mainly to responses in the antennules and eyes, whereas the differences observed in the chelipeds were less obvious, indicating that 110 V was insufficient to disrupt the posterior ganglion. In this instance it was difficult to evaluate the eyes as they became withdrawn into the carapace showing weak signs while moving them. There was no significant difference in probability of autotomy between voltage and current duration ($P > 0.05$, logistic regression; Table 2). However, keeping the crab in a fixed position over time resulted in heating and burn marks, increasing contact resistance and reduction of amperage flow (Figure 4).

Figure 4



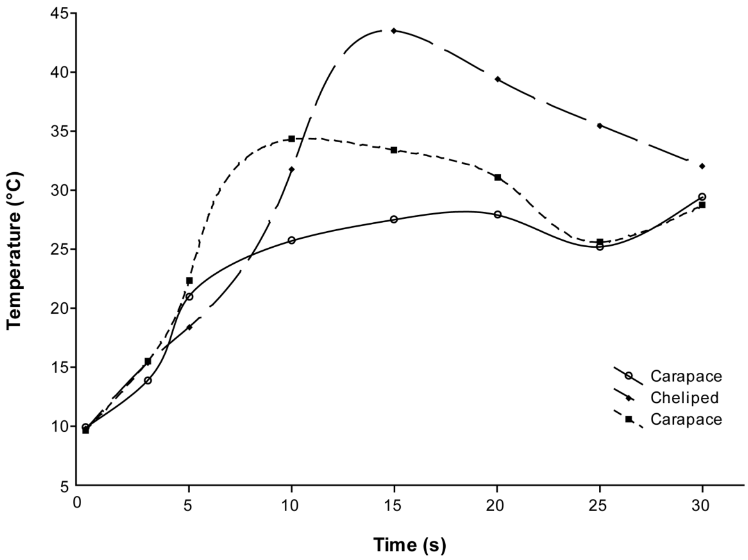
The ampere flow (y axis) through the crab as a function of time (s) (x axis). Each mark (d) represents a scale of 1 s, 50 V and 500 mA.

Therefore, a second trial was performed, where one crab was placed at a time into an electrical stunner and exposed to electricity while moving through the system with several electrodes. Table 2 shows significantly less autotomy ($P < 0.05$; Z-test) compared to crabs exposed to electricity in a fixed position.

Table 2 Behavioural score (Roth & Øines 2010) and autotomy of edible crabs (*Cancer pagurus*) exposed to 110/220 V of 50 HZ AC for 1, 5 and 10 s. The crabs were in a fixed position connected between the electrodes, while one group was exposed to electricity while being transported through a mesh of electrodes.

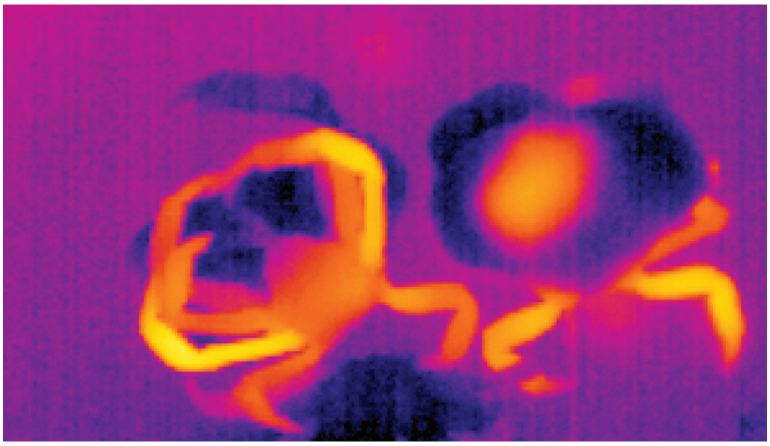
Voltage (V)	Current duration (s)	Behavioural score (0–8)	Number of crabs casting chelipeds/appendages		
			Probability autotomy	Total number lost	n
110	10	2.9	0.11	14	35
220		0.2	0.20	11	35
110	5	3.1	0.40	4	10
220		0.3	0.00	0	12
110	1	3.9	0.40	5	10
220		0.6	0.25	3	12
220	10 moving	0.3	0.07	3	43

Figure 5



The change of temperature at the contact area of electrodes during exposure of electricity at the carapace (n = 2) and chelipeds (n = 1).

Figure 6



Infra-red image of edible crabs (*Cancer pagurus*) exposed to 60 s of electricity in a fixed position.

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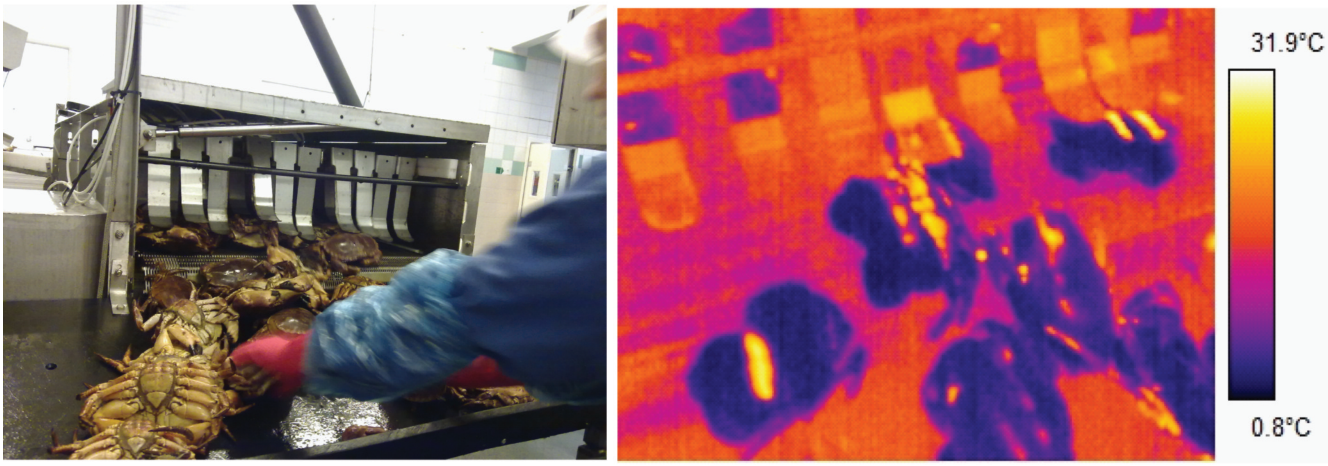
Figure 7



Prototype for dry-stunning of edible crabs (*Cancer pagurus*) (left) and infra-red picture of edible crabs (right) exiting the prototype after a 10-s current exposure.

Table 3 Mean (± SD) and min-max surface temperature (°C) of the entire crab measured with infra-red light spectrum. The crabs were untreated (Control) or exposed to 10 s of 220 V, 50 Hz AC (El-crab). The temperature was measured immediately after the electric exposure (t = 0 min) and after 3 min (t = 3 min).

	t = 0 min			t = 3 min		
	Min	**Max**	**Mean (± SD)**	**Min**	**Max**	**Mean (± SD)**
Control 1	5.3	8.8	6.4 (± 0.5)	5.7	8.9	6.9 (± 0.6)
Control 2	6.2	9.4	7.2 (± 1.0)	5.8	9.4	7.1 (± 0.5)
El-Crab 1	5.1	15.0	7.7 (± 1.5)	4.9	9.2	7.2 (± 0.6)
El-Crab 2	5.8	11.3	7.7 (± 1.0)	5.9	8.8	7.3 (± 0.5)
El-Crab 3	5.1	19.6	6.7 (± 1.4)	5.4	9.9	6.5 (± 0.7)
El-Crab 4	5.1	23.4	6.7 (± 1.5)	5.4	9.9	6.5 (± 0.7)
El-Crab 5	5.6	22.2	7.4 (± 1.0)	5.7	9.6	7.1 (± 0.6)

Phase 3 Commercial stunning of edible crabs

In accordance with Roth and Øines (2010), 30 min of live-chilling prior to stunning slowed down the responsiveness of the crabs, but did not render the animals insensible, thus all crabs were able to respond. Loss of responsiveness was therefore an effect of electrical stunning rather than chilling. All the crabs investigated that were exposed to 220 V for 10 s (n = 400) showed no appendage responsiveness immediately following electrical exposure, irrespective of whether the crabs were live-chilled or not. The commercial practice of placing crabs into freshwater failed to kill them quickly as 30% recovered within 60 min.

New sets of experiments were carried out where both live-chilled crabs and those held at ambient temperature were stunned and stored in ice slurry. Close examination of 30 crabs from each group over the following hour revealed that none showed any signs of recovery. A large-scale test of live-chilled crabs stored in ice slurry showed that none of the 271 crabs investigated showed signs of life after 30 min and then 1 h storage. If crabs are live-chilled prior to stunning, one possible solution is to store them in air providing that the air temperature is low. Of the 115 live-chilled crabs electrically stunned and placed in air, none recovered within the hour.

Instead of killing crabs by storing them in ice slurry or in air after stunning, a much more appropriate killing method would be to boil or carve the animal directly after stunning. This would be faster and more secure than any other attempts to kill them via asphyxia.

Although electricity is generally efficient at stunning food animals to render them incapable of feeling pain, the electric shock poses a degree of risk to the quality of the product. Results on autotomy showed that approximately 7% of crabs held at ambient temperatures either lost one appendage or cheliped, while the proportion of live-chilled crabs was 4% (n = 224; $P > 0.3$; Z-test). As well as stimulating nerves and forcing muscles to deplete the energy reserves (Chiba *et al* 1990; Roth *et al* 2010), a prolonged electrical current will cause over-heating. As shown in Figure 5, exposing the animal to electricity for 30 s or longer in a fixed position will cause substantial over-heating of the carapace, not to mention the appendages and chelipeds, if they are left in contact with one of the electrodes. Therefore, it is of paramount importance to reduce the effects of heating. Stunning in a fixed position will pose risks for localised over-heating affecting meat quality, not to mention higher contact resistance reducing the amperage flow (Figure 4). As shown in Figure 5, the temperature of the area of contact increases rapidly both in the carapace and chelipeds for the first 10–15 s. Thereafter, the contact resistance increases and the heat around the contact surface decreases (Figure 5). Although the heat reduces around the contact area, the amperage flow will continue to heat the crab. As shown in Figure 6, a 60-s exposure will cause substantial heating of the entire crab, especially the appendages and chelipeds. It is important, therefore, to have a moving system with many electrodes switching with a reduced current duration. As shown in Figure 7, exposing the crab to a 10-s current duration in a moving system causes some localised over-heating of the exoskeleton. Table 3 shows that crabs exposed to electricity will have localised areas in which the temperature reaches as high as 23°C. Three minutes later these levelled out and no significant difference in temperature could be detected between electrically treated and control crabs ($P > 0.64$; Repeated ANOVA). This clearly shows that the over-heating observed after a 10-s exposure to electricity is localised surface heating associated with contact resistance and not a generalised over-heating as a result of amperage flow through the animal, which requires longer current duration.

Conclusion

We conclude that electricity appears to be an efficient stunning method for edible crabs, as indicated by behavioural measures. The minimum amount of electricity required for stunning crabs within 1 s is 220 V. A 10-s current exposure is optimum to prolong unconsciousness and to avoid over-heating. Crabs should be processed immediately for killing and, if not, stored on ice or slurry to ensure that the animals remain unconscious until death ensues. Autotomy was not avoided, where approximately 4–7% lost one or more appendage. Since these conclusions are based on behavioural responses, we recommend that further studies are needed to establish an unequivocal loss of consciousness.

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