Stunning and killing of edible crabs (Cancer pagurus)

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Abstract

The stunning and killing efficiency of ice, superchilling (N_2 gas), freezing (–37°C), gradual heating (40°C), boiling, piercing of ganglia, salt baths (NaCl and KCl), gas (CO_2) and electricity (50 Hz AC) on edible crabs was studied. Results showed that electricity was the most efficient stunning method, whereby edible crabs could be rendered insensible within 1 s using electric field strengths of 400 V m^{-1} and above. Prolonging the electrical current to 10 s resulted in less potential difference (220 V m^{-1}) required to stun the crabs. Applying a two-stage stun with 530 V m^{-1} for 1 s followed by 170 V m^{-1} for 2 min resulted in a state of prolonged unconsciousness and 60% mortality. Failure to stun the crabs with electricity resulted in massive autotomy, where all appendages were lost. Behavioural responses were lost in approximately 30% of crabs after 100 min of chilling on ice, while freezing did not render the crabs unconscious until temperatures of subzero were reached. The exposed chelipeds stiffened, and once frozen, irreversible damage was caused. Placing crabs into heated seawater (40°C) led all responses to be lost after 5 min, while the internal temperature exceeded an average of 26°C, representing approximately 2.5 min of boiling. Gas, in the form of CO_2, NaCl, and a low concentration of KCl (5%), failed to render the animals insensible within 12 min. Using 20% KCl saw all animals lose all behavioural responses within 3 min. The piercing of single ganglions failed to kill the animal; both ganglia must be pierced in order to kill the animal. We conclude that electrical stunning is recommended prior to boiling or carving, while piercing can alternatively be carried out by trained personnel.

Keywords: animal welfare, edible crabs, electricity, killing edible crabs, stunning, temperature

Introduction

There is very little up-to-date information on how stunning and killing methods affect the welfare of decapods, despite this issue regularly being the subject of much public attention. Although crustaceans are not generally considered to have the capability to experience pain and thereby suffer (Elwood *et al* 2009), recent research has tended to support the notion that crustaceans do show avoidance learning to potentially painful stimuli (Elwood & Appel 2009). Concerns regarding the welfare of crustaceans during killing garnered much scientific attention in the middle of the 20th century (Sinel 1932; Aaser 1949; Baker 1955, 1962; Gunter 1961, 1962; Benarde 1962), when large lobsters were the focus as they are particularly hard to kill. The first report concerning the welfare of the European lobster (*Homarus gammarus*) was described in 1932 by Joseph Sinel (reviewed by Aaser 1949), who described that a gradual increase in temperature until boiling was the most humane killing method for lobsters; seemingly unconscious at 18°C and dead at 26.6°C. Aaser (1949) also described that lobsters placed directly into boiling water showed aversive behaviour and signs of life for approximately 58 s. Furthermore, he showed that destruction of the cerebral

ganglion had no effect as the lobsters showed signs of life for 70 s in boiling water. Also, Aaser (1949) showed that lobsters had aversive reactions to boiling, lasting up to 120 s, and that temperatures between 30–38°C managed to stun the lobster prior to boiling. Furthermore, Aaser (1949) concluded that salt brine stunned the lobsters within minutes and therefore would be the most humane stunning method. More recent research on the Australian giant crab (*Pseudocarcinus gigas*) shows that these large animals are not immobilised in chilled seawater, CO_2-saturated water or freshwater, but that the giant crab was sensitive to various anaesthetics, such as isoeugenol (AQUIS®, AQUI-S Inc, New Zealand) and chloroform, whereby AQUIS® would be the preferred choice in terms of welfare (Gardner 1997).

For the edible crab (*Cancer pagurus*), the most common stunning method is via a thermal shock with iced seawater (1–4°C) prior to carving and boiling. Chilling reduces the mobility of the crab, making the animal easier to handle, but also prevents the animals from injuring each other. More importantly, chilling prevents the animal from casting its chelipeds during boiling (Baker 1955). For killing, piercing of the ganglia can be performed on edible crabs, where the posterior ganglia are commonly destroyed. Piercing imme-

diately paralyses the animal, rendering it unable to move its extremities, but the eyes and mouth — which are connected to the anterior ganglion — do respond normally indicating that the animal is still conscious (Anonymous 1978). Another method used for killing and processing crabs is carving. Crabs are placed into machines, which rip off the appendages before the carapace is split in two, and the separate body parts are processed into food. Unfortunately, the lack of efficient stunning and killing methods often leads to live carving. Electricity is emerging as an interesting alternative as decapods appear stunned when immersed into an electric field (Anonymous 1999; Robb 1999), although it is unclear whether electricity can be considered as a killing method in addition to stunning. Also, asphyxia is currently used to kill decapods without boiling, using either salt brine or freshwater. The most common technique is via freshwater where death will occur after 3–5 h at 10°C and after less than 30 min at 38–49°C (Edwards 1979).

Currently, little information is available on the impact of various stunning methods on the welfare of decapods. The aim of this study was therefore to evaluate the stunning and killing efficiency of thermal shocks (heat and cold), salt brines (NaCl and KCl), gas (CO_2), piercing of ganglia and electrical stunning on edible crabs.

Materials and methods

During September 2006, in the Kvitsøy Islands, Norway, a total of 65 edible crabs weighing 416 (± 106) g were brought from the sea (10–12ºC) on a daily basis and transported to Nofima Norconserv A/S, Stavanger, Norway for early morning experiments. All procedures were approved by the Norwegian National Animal Research Authority who requested that a minimum of animals should be used. This explains the low number of crabs used in certain instances.

Methods used for stunning and killing

Piercing of ganglia

Two crabs had either their anterior or posterior ganglion destroyed with a stitching awl. This was carried out in accordance with the process outlined by Baker (1955). Behaviour was monitored during the subsequent 10 min before the animal was euthanised through piercing of the second ganglion.

Thermal shocking

In preparation for measuring internal temperature, the crabs were first killed by piercing anterior and posterior ganglia with a stitching awl. The holes were then glued with heat-resistant silicon to prevent leakage of hot water. Wireless TrackSense Pro™ temperature loggers (Ellab A/S, Denmark) were used to measure the internal temperature which was taken at the tip of a fixed sensor (94 mm long, 2 mm diameter) of the logger unit. The temperature of the claw was measured in the muscle of the manus, the most distant part of the cheliped, by penetrating the soft tissue of the joint. In order to measure the carapace temperature, a narrow hole was drilled in the groove covered by the abdomen on the ventral side. The sensor was inserted through this hole and positioned in the geometrical midpoint of the body. The loggers were taped to the body of the crab to ensure they remained in place.

Heat

In order to determine the temperature tolerance of crabs, in terms of withstanding heat, a total of seven were placed singly into 40 L aquaria containing 37–41ºC seawater. The behavioural score was noted after 2.5, 5 and 10 min of heating. After 10 min of heating, all the crabs were taken out and placed back into 12ºC seawater to monitor recovery. All except were two killed via piercing of both ganglia. For the two remaining crabs, loggers were placed into the carapace and claws before they were placed back into the heated water to log internal temperature.

Boiling

Here, the internal temperature was monitored in the carapace of three dead crabs. Since the reaction of crabs during boiling has been well described (Baker 1955), plus the inherent difficulties involved in performing more detailed behavioural analysis, it was decided not to boil any live crabs.

Chilling

To determine temperature tolerance of crabs as regards chilling, a total of seven were placed in a polystyrene box containing ice (0ºC) and behavioural responses were analysed at intervals of 20 min. After 100 min, the crabs were placed back into 12ºC seawater to measure recovery, before three were killed and temperature probes placed in the carapace and claws and the experiment was repeated measuring internal temperatures under the same chilling condition.

In addition, five crabs were placed into a –40ºC freezer and behavioural responses noted at 10-min intervals until all behavioural responses were lost, before being removed and placed into 12ºC seawater to measure the following recovery and death.

In order to create a thermal shock related to chilling, six crabs were placed into a superchiller (AGA-freeze-mini nitrogenfreezer, AGA, Norway) and exposed to –60°C deliquidised nitrogen gas for 3.2 min. Half of the crabs (n = 3) were immediately placed into 12ºC seawater to thaw and be monitored following recovery, while the other half were placed on the table allowing the low temperature to continue to slowly infiltrate the crabs.

Bathing

Edible crabs at approximately 12ºC were placed singly into a 10 L aquarium containing 17% NaCl (n = 1) solution, 5% KCl (n = 1) or 20% KCl (n = 3) solution. For CO_2, a total of six crabs were placed into a 60 L tank filled with seawater, fully saturated with CO_2, providing a pH of 5.1 and $pO_2 < 2$ mg L^{-1}. Behavioural responses were analysed from 0 to 12 min. Previous work by Edwards (1979) had revealed very long stunning and killing times using freshwater, therefore this was not evaluated in the present study.

Electrical stunning

For electrical stunning, a total of 26 crabs were placed into a 50 × 27 × 30 cm (length × width × height) glass tank of seawater (CI = 54,000 μS cm^{-1}) between two 26.5 × 40 cm (width × height) steel electrodes, 30 cm apart. The primary circuit for the power inlet was industry standard 380 Vrms, 3 phase, 50 Hz, AC using 60 A fuses, which was capable of providing approximately 23 kW. The secondary circuit was connected to an isolated variable AC transformer (Variac) amplifying one-phase sinusoidal 50 Hz AC from 0 to 220 Vrms. The current duration was regulated using a time relay (1–10 s). For the experiments, crabs were exposed to 50 Hz, sinusoidal AC with electric fields equivalent to 170–530 V m^{-1}. To monitor the potential difference from the amplifier, a Micronta auto range digital multimeter (Radioshack C/O, TX, USA) was used, while a Fluke 123 Industrial Scopemeter (Fluke Inc, Everett, WA, USA) was used to monitor and log the potential difference across the tank. After stunning, behavioural responses were noted and the following recovery was monitored with time.

To test whether crabs could be killed by electricity, 10 crabs were electrically stunned using a two-stage stun, whereby each crab was exposed to 530 V m^{-1} for 1 s and then 170 V m^{-1} for 2 min. After stunning, behavioural responses were then monitored every 10 min for 60 min to check if the crabs had recovered or not.

Behavioural responses

Since crabs have series of ganglia clustered into two major ganglia, behavioural responses from i) eyes, antenna and antennules or ii) appendages and the mouth were used to test the sensory and locomotory reactions related to the i) anterior and ii) posterior ganglia. The degree of consciousness was evaluated based on responses of these body parts (Baker 1955; Gardner 1997). For other ectothermic animals, such as fish, the degree of consciousness can be determined not only by loss of certain reflexes, but also the degree to which they are lost (Kestin *et al* 2002). Also, environmental factors, such as temperature, are known to prevent the animal exhibiting basic reflexes (Roth *et al* 2009). We therefore defined a new protocol (Table 1) evaluating not only the existence of certain behavioural responses, but also the degree to which they respond, quantified into 3 levels: 0) no response; 1) weak response; and 2) normal response. Behavioural responses focused on the appendages/chelipeds, mouth, antennules and eyes, representing two behavioural responses from the posterior and anterior ganglia, respectively. All these behavioural responses were then summarised providing a consciousness score on a scale from 0–8.

To quantify death, after stunning, the crabs were placed back in their environment and if no signs of recovery were observed within the following 60 min, the crab was classified as dead.

Statistical analysis

To analyse continuous and dependent variables and temperature relative to time, log linear regression was used as a statistical model. The independent variable was log-transformed and plotted to test a linear relationship and residuals were plotted to check if they were normally distributed. For testing differences between slopes, Student's *t*-test was used. For testing parametric variables, such as behaviour score against two variables, the Mann-Whitney *U* test was used, while multiple comparisons of rank (MCR) were used for three or more variables. In order to estimate the slope at which the behaviour scores changed during stunning, stepwise regression was used as a regression model. The Student's *t*-test was used for testing the difference between the slopes and the intercept (α) was tested against the normal behavioural score = 8 at *t* = 0. The probability (*P*) was estimated by *t*α/2 at df = n–2.

Results

Piercing of ganglia

For piercing, the crab that had its anterior ganglion destroyed lost the ability to show eye and antennule responses but the appendages maintained normal activity, with the crab walking around and systematically trying to protect itself from tactile stimuli with the chelipeds. Similarly, with destruction of the posterior ganglion, the crab lost the ability to move and protect itself, but the eyes and antennules maintained normal behaviour, retreating into sockets if threatened and re-emerging to smell, taste and study its new environment. After 10 min, none of the crabs showed any signs of dying, so the experiment was terminated and the crabs euthanised by piercing the second ganglion.

Thermal shock

Placing crabs into 40ºC seawater (Figure 1) showed that the internal temperature of the carapace rose at a rate of $\beta_{carapace} = 14.69 \times Log(t + 1_{min})$ ($P < 0.005$, $r = 0.99$, log linear regression; Figure 1). The temperature rise in the claws was significantly higher than in the carapace ($P < 0.0005$, *t*-test) at a rate of $\beta_{claw} = 17.47 \times Log(t + 1_{min})$. This had an effect on live crabs, where the behavioural responses of the chelipeds were already significantly reduced after 2.5 min ($P < 0.05$, Mann-Whitney *U* test; Table 2). The crabs decreased their behavioural score at a rate $5.6–0.70 \times t_{min}$ ($P < 0.0005$, stepwise regression; Table 2), where the model failed to intercept within a score of 8 ($P < 0.0005$, Student's *t*-test). After 5 min, all crabs with the exception of 1 had lost all signs of life and this last remaining crab lost all responses within 10 min. The average core temperature of the crab was approximately 26.8 (± 3.2)ºC at 5 min, indicating that crabs lose consciousness within a 12–14°C temperature rise. Placing the crabs back into 12ºC seawater saw all individuals start to recover within 5 min, doing so fully within 10 min.

Table 1   Protocol for scoring conditions of consciousness in the edible crab. Behavioural score is given on the responsiveness (0–2) of the i) eyes, antennules and ii) appendages and mouth representing the anterior and posterior ganglia. Summarising the behavioural score will quantify the degree of consciousness in the crabs on a scale from 0 to 8.

Ganglion	Part of anatomy	Behavioural score		
		Normal response (2)	**Weak response (1)**	**No response (0)**
Anterior	Eyes	Eyes respond to visual stimuli by lowering into sockets in the carapace and then re-emerging	The eyes remain hidden in the sockets but responses still visible after touching	Eyes show no response to stimuli and drop out of sockets when crab is inverted
	Antennules	Vigorously emerging to smell and taste the new environment and protecting antennules by folding into sockets on tactile stimuli	Often withdrawn into sockets; when lifted out antennules are slowly retracted into sockets	Antennules remain out after lifted from sockets
Posterior	Appendages	Actively trying to escape and protect itself while touching the apron	Weak response or complete failure to walk or protect itself; claws show no general response but resist being forced open	No response; claws can be forced open with no resistance
	Mandibles/ maxillipeds	Normal response and resists opening	Weak response; maxillae can be opened but fall back into closed position	No response; mandibles remain open when forced

Figure 1
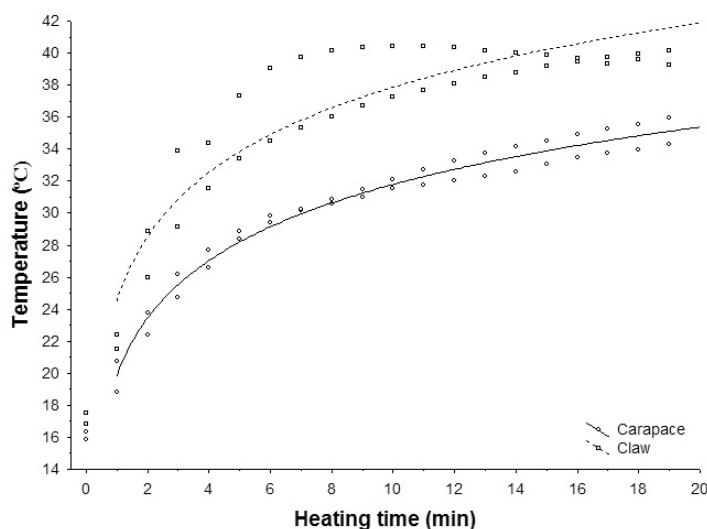
Log linear regression of the internal temperature of the carapace (solid line) or chelipeds (dotted line) in two edible crabs taken from 16°C and placed into 40°C seawater.

Taking crabs from 12ºC and placing them into boiling water saw the internal temperature rise at a rate of $\beta = 65.14 \times \text{Log}(t + 1_{min})$ ($P < 0.0005$, $r = 0.98$, log linear regression; Figure 2). Taking into account results from Table 2, which showed that crabs lost consciousness when the internal temperature exceeded 26°C, gives the equivalent of 2.5 min of boiling (Figure 2).

Placing the crabs on ice (Figure 3) showed that all responses ceased gradually at a rate of $6.9–0.058t_{min}$, ($P < 0.0005$, stepwise regression; Table 2) starting with the exposed appendages and eyes, followed by the mouth. The intercept failed to within normal range ($P < 0.005$, Student's t-test). Of the seven crabs chilled for 100 min, two reached a score of 0, while two reached a score of 1 and 2, respectively and

three attained a score of three. The internal temperature at that point was 1.8ºC. All crabs fully recovered within 10 min after being placed back into 12ºC seawater. The internal temperature of the crabs at that point was 4 to 5ºC.

Placing the crabs into the –37ºC freezer saw crabs lose their behaviour score at a rate of $7.5–0.17t_{min}$ ($P < 0.0005$, linear regression; Table 2), where the intercept was within the normal score of 8 ($P > 0.07$, Student's t-test). The exposed appendages were significantly affected after 10 min and lost within 20 min (Table 2). It took approximately 30 and 40 min until the behaviour responses were lost for the eyes, mouth and antennules, respectively (Table 2). In terms of recovery, it appears that once the exposed appendages were frozen, irreversible damage was caused, prohibiting the

Table 2   The average behavioural scores (0–8) of edible crabs placed in heated seawater (40°C; n = 5), in polystyrene boxes containing ice (0°C; n = 7) or in the freezer (–37°C; n = 5).

Time (min)	Behaviour score (0–8) in median (25–75 percentiles)		
	Heating (40°C; n = 5)	Chilling (0°C; n = 7)	Freezing (–37°C; n = 5)
0	8 (8–8)	8 (8–8)	8 (8–8)
2.5	4 (2–5)	–	–
5	0 (0–0)	–	–
10	0 (0–0)	6 (4–7)	6 (6–7)
20	–	–	4 (2–4)
30	–	–	I (I–I)
40	–	4 (4–5)	0 (0–0)
60	–	3 (2–3)	0 (0–0)
80	–	3 (I–3)	–
100	–	2 (0–3)	–
β	–0.70[a]	–0.058[b]	–0.17[c]

Different superscripts represent significant differences, at the level of $P < 0.0005$, between the slope (β) in which behavioural responses were lost.

Figure 2

Log linear regression on the internal temperature of the carapace in three edible crabs taken from 16°C and placed into boiling water.
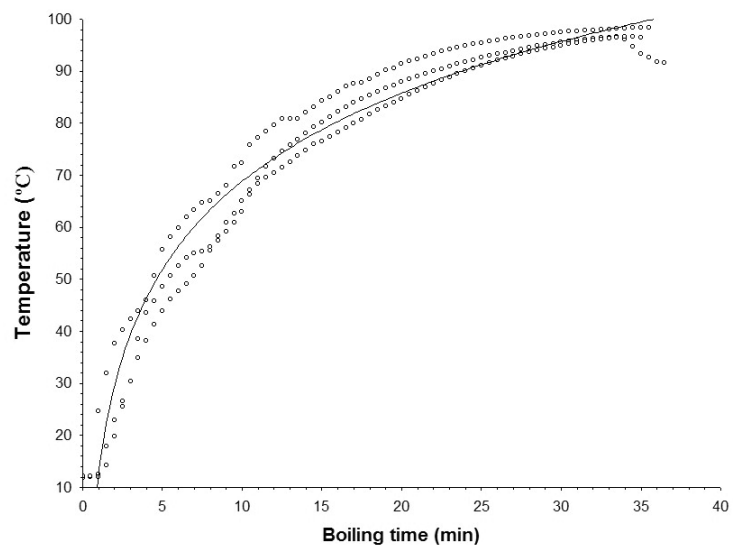
Figure 3

Log linear regression on the internal temperature of the carapace (solid line) or chelipeds (dotted line) in three edible crabs taken from 14°C and placed into polystyrene boxes containing ice at 0°C.
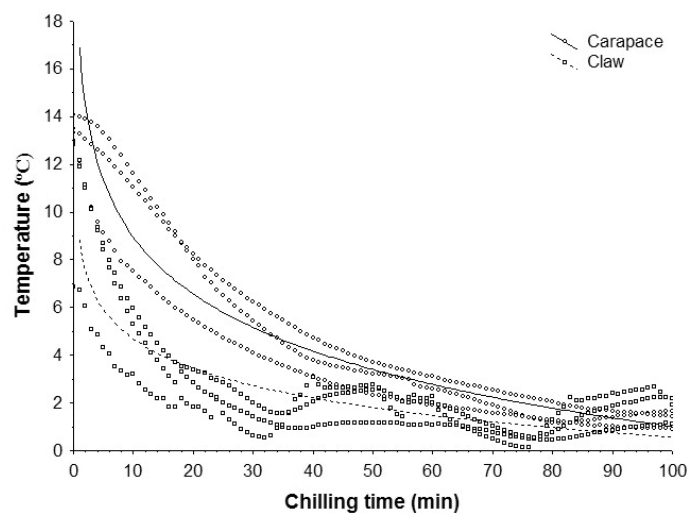
Table 3   Average behavioural score (0–8) and slope (β) for which behavioural responses were lost in edible crabs stunned in water baths containing salts (17% NaCl, 5% and 20% KCl) or gas (CO_2).

Time (min)	Behaviour score (0–8) in median (25–75 percentiles)			
	CO_2 (n = 6)	5% KCl (n = 1)	20% KCl (n = 3)	17% NaCl (n = 1)
0	8 (8–8)	8	8 (8–8)	8
1	8 (8–8)	8	2 (0–2)	8
3	6 (6–6)	8	0 (0–0)	8
8	4 (0–4)	–	0 (0–0)	–
12	0 (0–4)	–	0 (0–0)	–
β	–0.63	–	–0.66	–

Table 4   Behavioural scores (0–8) of edible crabs exposed to various electric field strengths (V m^{-1}) and current durations (s) and subsequent recovery.

Electrical settings	Lost appendages	Average behavioural score (0–8) in median (25–75 percentiles)							PR	
		0 min	5 min	10 min	15 min	20 min	40 min	60 min	P-value	n
530 V m^{-1}, 1 s	3 from 2 crabs	0.0 (0.0–1.0)[a]	8.0 (6.0–8.0)[a]	–	–	–	–	–	1.0	10
400 V m^{-1}, 1 s	2 from 1 crab	0.0 (0.0–3.0)[a]	8.0 (5.5–8.0)[a]	–	–	–	–	–	1.0	4
230 V m^{-1}, 1 s	All	8.0 (8.0–8.0)[b]	–	–	–	–	–	–	1.0	2
230 V m^{-1}, 10 s	4 from 3 crabs	0.0 (0.0–0.0)[a]	1.5 (0.0–2.0)[b]	2.0 (1.0–5.0)	4.0 (2.0–6.0)	6.0 (3.0–8.0)	–	–	0.9	10
530 V m^{-1}, 1 s + 170 V m^{-1}, 120 s	None	0.0 (0.0–0.0)[a]	0.0 (0.0–0.0)[c]	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	0.0 (0.0–4.0)	0.4	10

In each column different superscripts represent significant differences at $P < 0.05$.
PR: Proportion recovering.

animal from expressing behavioural signs, despite recovering. After 60 min in the freezer, none of the crabs showed any signs of recovery, ensuring death. In all cases autotomy did occur, casting two or more appendages.

None of the six crabs exposed to superchilling showed any behavioural signs on exiting from the machine. When three crabs were placed into 12ºC seawater, causing them to thaw, all expressed eye and antennule responses within one minute. For the appendages, irreversible damage was caused as freezing prohibited the expression of behavioural responses. Autotomy of two or more appendages was observed for all animals. The three remaining crabs that were not quickly thawed did not regain any behavioural responses suggesting that the freezing layer moved towards the internal parts of the animal.

Bathing

When placed into salt brine (Table 3) containing 17% NaCl or 5% KCl, crabs expressed aversive behaviour, vigorously trying to escape. The crab exposed to 17% NaCl solution did calm down after 2 min, but all reflexes were present, although weakened. When the crab exposed to 5% KCl did not show signs of calming after 3 min, the experiment was terminated and the crab was removed and euthanised.

The crabs exposed to 20% KCl made no attempt to escape and lost their reflexes at a rate of $4.4 - 0.66 \, t_{min}$ ($P < 0.0005$, stepwise regression; Table 3). The intercept was significantly lower than the normal score ($P < 0.0005$, Student's t-test). Within 1 min, the crabs lost all cheliped responses and there were reduced responses from the eyes and mouth. Within 1.5 min all three crabs had lost all their reflexes.

For CO_2 (Table 2), the crabs showed aversive behaviour and the reflexes were gradually lost over time at a rate of $8.06 - 0.64 t_{min}$ ($P < 0.0005$, stepwise regression). The intercept was within normal range ($P > 0.6$, Student's t-test). After 12 min, four crabs had lost all reflexes, while two still showed weak responses related to the anterior and posterior ganglion.

Electrical stunning

A failure to stun the crabs within 230 V m^{-1} for 1 s did cause a massive autotomy, whereby both crabs tested lost all their appendages, including chelipeds (Table 4). The crabs were fully conscious expressing normal behaviour as regards the eyes, antennules mouth and stumps. Increasing the electric field strength to 400 V m^{-1} did not cause significantly lower behavioural score as compared to 230 V m^{-1} ($P > 0.08$, MCR), where three of the four exposed crabs lost all behavioural responses, while the other lost the ability to move the

chelipeds, but was able to express normal behaviour from the eyes and antennules (Table 4). This crab also lost two appendages. Improvement was observed ($P < 0.05$, MCR) on increasing the electric field strength to 550 V m^{-1}, where all 10 crabs lost every behavioural response related to the posterior ganglion, while three had normal responses related to the anterior ganglion (Table 4). Of these ten crabs, one lost one appendage, while another lost two, both crabs were successfully stunned. All crabs recovered fully within 5 min.

Increasing current duration to 10 s (Table 4) showed that all crabs (n = 10) were sufficiently stunned at 230 V m^{-1} as compared to 1 s ($P < 0.0005$, Mann-Whitney U test), with no behavioural responses observed in any of the crabs. Within 5 min, behavioural responses began to re-appear with weak antennule (n = 3) or mouth (n = 3) responses, continuing with the eyes and, finally, the chelipeds. One crab did recover fully within 10 min, while another recovered within 15 min. Of the eight remaining crabs, two had fully recovered within 20 min, while five others showed weak signs of life. One crab never showed any sign of life. Two crabs cast one appendage each, while a third lost two.

Attempts to kill the crab with a two-stage stun (n = 10; Table 4) resulted in failure to kill all animals as two crabs recovered fully within 60 min. In addition, one crab expressed normal responses related to the posterior ganglion, while responses related to the anterior ganglion were absent and *vice versa* on another crab. Results with the two-stage stun showed that it took almost 40 min before the first reliable signs of recovery were observed, significantly better than a 10-s stun duration ($P < 0005$, Mann Whitney U test). No appendages were lost during this process. Testing the proportion of appendages lost between the two-stage stun and crabs exposed to 550 V m^{-1} for only 1 s, showed no significant differences ($P > 0.08$, t-test).

Comparing the results from Tables 2, 3 and 4 shows that the effectiveness of each stunning method, based on regression models, can be ranked as: electrical stunning < 20% KCl < heated water < CO_2 < freezing < chilling, taking an average of 1 s, 6.6, 8.04, 12.7, 43, and 119 min, respectively, to reach a behavioural score of 0.

Discussion

Taking into account each of the commercial stunning and killing methods tested, all failed to a certain extent to stun the animal, causing either stress or a complete inability to stun the animal. The exposed appendages became paralysed long before any reasonable change in the crab's internal condition. From an animal welfare point of view, these results are the cause of considerable concern since the methods that proved the least efficient are also amongst the most common, commercially. This leads us to query whether these methods can be considered unethical since crabs may very well have the capacity to suffer pain. Although crustacea have a central nervous system (CNS) consisting of a series of ganglia inter-connected by a ventral nerve rather than one brain, there is evidence that crabs can experience stress and pain and, furthermore, that they have the cognitive capacity to remember and learn to avoid unpleasant stimuli (Elwood *et al*

2009; Elwood & Appel 2009). Whilst this provides ample justification for the study we have chosen to undertake, there remain questions to be answered concerning how one defines the conscious state of the crab. The complexity of having a differentiated CNS creates uncertainty when it comes to distinguishing differences between sensory and motor responses and thereby an overall certainty that the animal is insensible or at least unaware of the situation. Decapods would appear to have limited peripheral neurons for synaptic responses between sensory and motor fibres, where synapses are mostly located centrally in the CNS (Laverack 1988). This gives reason to believe that a physical response towards tactile stimuli is a reliable indicator of intact ganglia rather than merely a reflex. Unlike the motor system, the sensory system in decapods is complex, where the axons are mostly linked to specific ganglia, but also through a greater number of interneurones (Laverack 1988). This brings uncertainty as to where consciousness, fear and pain experience is located anatomically as the anterior and posterior ganglion can appear to function independently of each other. One example, for instance, would be our results, which showed that crabs could express normal behaviour related to the intact ganglion, independently from the other which had been physically destroyed. Although the posterior ganglion can be regarded as the main body of the CNS, the cognitive capacities along with awareness, consciousness and pain may, as far as these authors are concerned, be scattered. This provides a degree of challenge in terms of defining unconsciousness in the animal, unless the whole CNS is immobilised, validating the given score of consciousness (Table 1).

Electrical stunning turned out the most efficient stunning method for edible crabs. With sufficient electrical current the animal could be rendered unconscious within 1 s, thereby meeting legal demands from the EC for stunning mammals, poultry and fish (EFSA 2004). Stunning crabs in seawater would appear to pose many challenges as the electric field strength required to stun a crab for 1 s in seawater was almost three-fold compared to marine fish, requiring only 100–150 V m^{-1} for salmon, pollack and herring (Robb & Roth 2003; Roth *et al* 2004; Nordgreen *et al* 2008). For water-bath stunning this could present a problem, since it would require an impractically high level of current to stun large batches; it may be that dry stunning represents a better solution. Soaked in seawater and using a large sponge as an electrode placed on the carapace, Robb (1999) showed that edible crabs could be stunned with 110–150 V m^{-1} AC of electricity for 5 s with currents as low as 1.29 A. In accordance with Robb (1999), our results show that crabs cannot be killed with electricity.

Present day stunning and killing is often achieved by first chilling the animal before it is boiled or carved. Regarding boiling, questions arise as to how long a crab can sense heat for. Previous results on the gradual heating of edible crabs (Baker 1955) and lobster (Aaser 1949) (not being aware of the internal temperature at the time) showed that both animals were live and active at water temperatures above 20°C, but that lobsters lost responses at 28°C, while the edible crabs did so at 38–40°C. Our results on internal temperature during boiling suggest that the crabs can sense

heat for at least 2.5 min (Figure 2). Apparently, a cold shock can stun edible crabs, and previous research on blue swimmer crabs (*Portunus pelagicus*) has shown that a cold shock for 30 s or more will pacify the crabs, even killing them if extended for long enough (Bellchambers *et al* 2005). More important is the fact that the crabs regained their senses very rapidly when heated. This brings us to the essential question of the extent to which the welfare of crabs is affected by combining chilling with boiling. A crab chilled from 14 to 2°C prior to boiling will, roughly based on the model in Figure 2, be able to sense heat for at least 3 min.

As an alternative to boiling, piercing of the posterior and anterior ganglia has been recommended for edible crabs (Baker 1955). As demonstrated in this study, for the animal to be regarded as unconscious and dead, both ganglia must be destroyed, but it would still take 5–10 s for this procedure to be completed, hence it cannot be described as providing immediacy in terms of stunning or killing. Piercing the anterior ganglion requires great precision as any sort of deviation from the required sticking angle leads to an insufficient kill (Baker 1955). This precludes the use of this technique for all but the most skilled of personnel. This risk to the potential well-being of the animal becomes even greater prior to boiling.

In many instances, boiling the whole animal is inappropriate and, depending on the end product, animals are often carved up live via machine; appendages are ripped off and the carapace, ultimately, is split in two (Roth, personal observation 2005). This demonstrates the importance of separating the events of stunning and killing. For vertebrates, death is ensured by exsanguination or decapitation while, for crabs, we can only achieve similar effects by causing disruption to respiratory function unless we boil, freeze, superchill, pierce or crush them. Whether anoxia after electrical stunning would ensure insensible death is uncertain and needs to be studied in greater detail, but our results on CO_2 stunning under hypoxic conditions indicate that 12 min is an insufficient time for killing. As shown in Table 2, a possible alternative might be potassium chloride which is already known to cause cardiac arrest in lobsters (Battison *et al* 2000). However, as with heat and chilling, elevated potassium levels are known to cause muscle paralysis in mammals (Sandow & Kahn 1952) which, in this instance, would undermine the use of behavioural responses to determine animals' level of consciousness. Both NaCl and CO_2 have long been used to stun and kill aquatic animals, including edible crabs, but in line with Baker (1955) and Gardner (1997), we found these methods to be unsuitable for rendering the animals insensible. One possible solution for killing would be superchilling, rapidly chilling the animal to subzero temperatures before any chance of recovery. How KCl and superchilling affect taste and product quality is not yet known and would require further study.

Conclusion

These results demonstrate a number of the challenges of stunning and killing edible crabs, pointing out that they may be easily stunned with electricity, hence improving meat quality. However, no rapid killing methods exist, other than piercing the ganglia or boiling. Death by asphyxiation or

thermal shock/superchilling in combination with electrical stunning should therefore be studied. We recommend electrical stunning for commercial practices, while piercing can alternatively be carried out by trained personnel.

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