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Electrical stunning of pigs: the effect of applied voltage on impedance to current flow and the operation of a fail-safe device

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Abstract

The concept of a 'fail-safe' device to ensure that sufficient current is delivered to render a pig immediately unconscious when electrically stunned was investigated. For live pigs, no significant correlation could be determined between the pre-stun low voltage sensed impedance and the actual, higher voltage stun impedance. In contrast, a good correlation was found using heads from pigs killed more than 24 h previously. The impedance of a live pig's head was predominantly a function of the stunning voltage and decreased non-linearly with increasing voltage. The 'difference' between live and dead pigs was attributed to an 'ageing effect' which is not significant in the first few hours post mortem. No change in phase angle between corresponding stunning current and voltage waveforms, indicated that tissue reactance was not a contributing factor. It is concluded that 'fail-safe' devices based on low voltage pre-stun sensing are unlikely to meet the current legislative requirements (Council Directive 93/119/EC).

Keywords: Fail-safe; Electrical stunning; Voltage; Current; Impedance; Phase-angle

1. Introduction

When animals are electrically stunned it is important that enough current is passed through the brain to cause immediate loss of consciousness (MAFF, 1995). For pigs, this current is either a minimum of 0.41 A if the electrodes are placed in the optimal position (Anil, 1991) or 1.3 A if placed in the least optimal position (Hoenderken, 1978). A survey of commercial practice in the UK (Anil, McKustry, & Wotton, 1997) showed that many pigs failed to receive enough current and were therefore ineffectively stunned. The UK Government responded to the results of the survey by issuing guidance notes for good practice and amending the relevant legislation (MAFF, 1990). The amendment, which became effective on 5 July 1992, required electrical stunning equipment to deliver sufficient current to render the animal immediately insensible to pain. Electrical stunning equipment was required to be fitted with a device that would prevent it from delivering a current below that which it was set to deliver. This requirement has been referred to as providing a so-called 'fail-safe' device (Wotton & Whittington, 1994) and was also included in the provisions of Council Directive 93/119/EC.

How any 'fail-safe' device should operate was described by Wotton and Whittington (1994). Essentially, a very low sensing voltage would be used to estimate the impedance of the animal's head and this estimate used to determine whether the passage of the stunning current would be sufficient to produce an effective stun. If the impedance were too high the 'fail-safe' device would prevent passage of the full stunning current so protecting the animal from the pain and suffering which would ensue from an ineffective stun.

The work described in this paper investigated the relationship between the sensed impedance and the actual stunning impedance. In living pigs, this relationship was found not to be good enough to comply with the legislative requirements. Moreover, the application of high stun voltage was found to cause a breakdown in

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the tissue impedance between the electrodes which continued to decrease with stun duration.

2. Methods

2.1. Experiment 1

First, the performance of a prototype Stun Assurance System (SAS, Hellenic Systems Ltd., South Woodham Ferrers, UK) was examined to evaluate the principles of the 'fail-safe' concept. The SAS was used in conjunction with a high voltage 'Cash' electrical Stunner model ES1 that was configured to measure the sensed impedance between the tong electrodes within a pre-set, variable time window of 50 – 200 ms, using a 12 V d.c. sensing voltage. The pre-set, variable time window was selected to span the range in time (100–150 ms) necessary for animal to detect a painful stimuli (Wotton, 1996). In practice, this would enable the measurement to be made before the pig could detect the potentially painful application of the stunning electrodes. The 'Cash' stunner produced a square waveform a.c. at about 350 volts which consistently delivered >1.3 amps at 380 Hz for 4.5 s followed by a lower frequency current at 80 Hz. The pre-stun impedances measured were subsequently used to calculate predicted stun current values. Electronic monitoring by the SAS enabled data for the sensed impedance, the predicted current level and the stunning current profile of each animal to be calculated, stored in memory and subsequently downloaded to a laptop computer for further analysis. First the SAS, hardwired to the 'Cash' electrical stunner, was tested on dead pigs' heads to compare predicted current with stunning current and then subsequently installed in a commercial pig abattoir to collect data on-line, from all the animals killed in one day ($n=477$). The stunning electrodes were applied manually to the heads of pigs free standing in a stunning pen.

2.2. Experiment 2

More sensitive bench test equipment was used to make similar measurements to those made in experiment 1 in a second commercial trial, using a 25 V d.c. sensing voltage and a 120 Ω sampling resistor in series with the tong electrodes. Unlike experiment 1, in this experiment the high stunning voltage was switched on via a transistorised relay when the applied pressure between the electrodes exceeded 5 kg. The latter was measured via a pressure transducer mounted on the arm of the stunning tong attached to one electrode. Providing a pressure of 5 kg was exceeded, the stunning voltage was maintained. When the tongs were removed and the pressure fell below 5 kg, the low voltage d.c. sensing was reapplied. A differential voltage probe and a fast response current probe were used to record voltage and current profiles. The pressure, voltage and current were all recorded simultaneously on a TEAC FM tape recorder and observed during measurement on a digital oscilloscope (LeCroy, Abingdon, UK).

Further analysis of the current and voltage profiles enabled corresponding current and voltage waveforms to be examined in more detail. In particular, expanded waveforms were inspected on an oscilloscope to investigate whether there was any difference in phase between the current and voltage waveforms arising from tissue reactance.

2.3. Experiment 3

The effect of stunning voltage magnitude on the impedance of pigs' heads was investigated. A range of voltages was selected (50–350 V rms) to investigate the electrical parameters of the stunning operations. Anaesthetised pigs were used in this experiment because the lower voltages applied would have been insufficient to induce an effective stun. Six pigs, of approximately 70 kg live weight, were sedated with an intramuscular injection of 100 mg Ketamine (Fort Dodge Animal Health Ltd., Southampton, UK) per 10 kg live weight, anaesthetised with halothane, intubated and ventilated mechanically with 3:1 nitrous oxide:oxygen plus sufficient halothane to maintain deep anaesthesia. The pigs were restrained in a hammock for the duration of the procedure.

Stunning tong electrodes were applied manually to the pig's head and connected to the output of a variac transformer (VA 2100, Louth Transformer Co. Ltd., Louth, UK). The applied pressure (maintained at approximately10 kg), corresponding voltage and current profiles were recorded as described in experiment 2. The voltage (50 Hz sinewave a.c.) was increased from 0 volts to about 350 volts and then decreased back to zero volts over a total application time of about 8 s. Each pig was killed at the end of the experiment by electrically-induced ventricular fibrillation, without recovery of consciousness.

2.4. Experiment 4

The ageing effect post mortem on the impedance to stunning current flow was investigated using the six pigs in experiment 3. This involved the application of a fixed stunning voltage of 300 volts at 50 Hz a.c. sinewave for 2 s at an application pressure of 10 kg to each pig immediately prior to the electrical induction of a cardiac arrest through ventricular fibrillation and sequentially at a range of times up to 24 h post mortem. The corresponding applied pressure voltage and current profiles were recorded as described in experiment 2.

3. Results

3.1. Experiment 1

When the SAS was applied to dead pigs' heads, statistical analysis (Pearson correlation) indicated a good correlation ($r = 0.96$) between the predicted current (calculated from the sensed impedance) and the steady stunning current (Fig. 1). In contrast, analysis of the data obtained from live pigs in the commercial trial (Fig. 2) demonstrated that on average the predicted current was only 35% of the steady stunning current but with considerably more variation than in the dead animals ($r = 0.43$). The correlation with the sensing impedance in live pigs was therefore too poor to meet the legislative requirements.

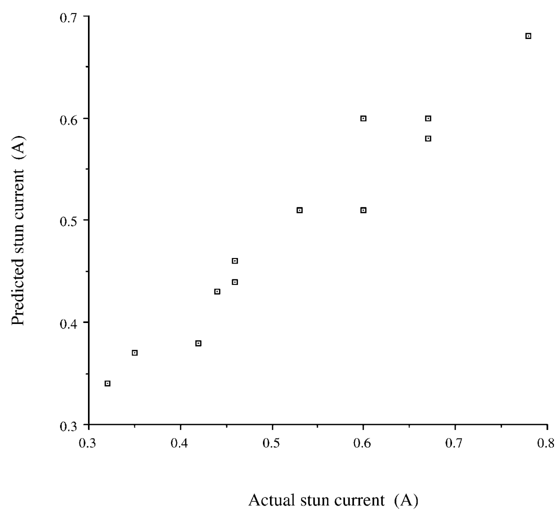

Fig. 1. Experiment 1: predicted stun current vs actual current for dead pigs.

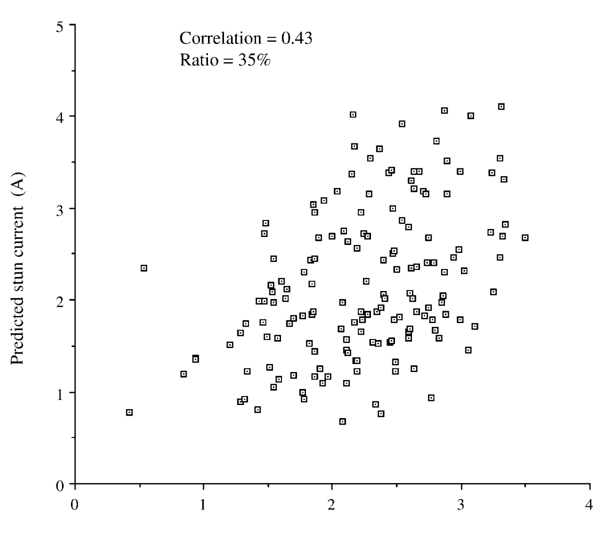

Fig. 2. Experiment 1: predicted stun current vs actual current for live pigs.

3.2. Experiment 2

The measurements carried out in experiment 1 on dead pigs' heads were repeated using more sensitive bench test equipment and showed that the current profile from a typical dead pig's head (Fig. 3) showed different characteristics from those obtained with a live pig (Fig. 4). The current measurements for the dead pigs resemble the profile obtained when using a standard resistor in place of the pig but, the profile obtained from a live pig showed a more pronounced rise in current amplitude with time, during the stun. The results from a second commercial trial were analysed and the best correlation was obtained by using the method of a running mathematical average. The stunning current (I_{start}) at the beginning of the stun was measured using the first complete cycle at approximately 20 ms after the 25 volt sensing was switched off. The results are illustrated in Fig. 5. These showed that, on average, the predicted current was 42% of the actual current at the beginning of the stun with a Pearson correlation of $r = 0.80$. The correlation between the I_{start} and the more steady current measured later in the stunning period (I_{stun}), was poorer ($r = 0.46$) (Fig. 6).

Analysis of the corresponding current and voltage waveforms for the data obtained showed no significant change in phase angle between the two waveforms. An

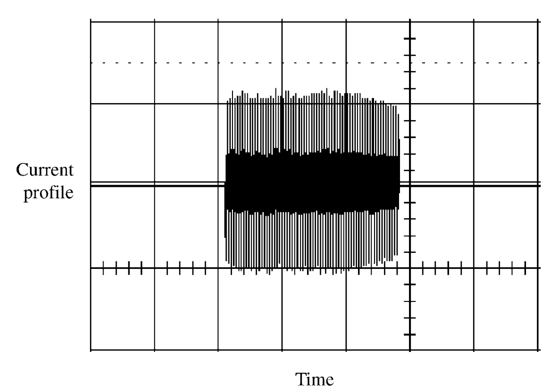

Fig. 3. Experiment 2: typical stun current profile from a dead pig.

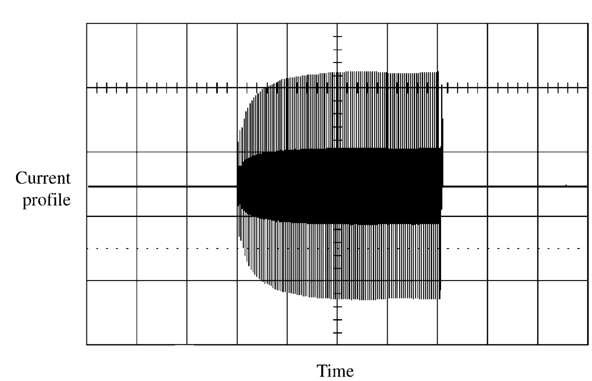

Fig. 4. Experiment 2: typical stun current profile from a live pig.

example of the expanded waveforms for a typical pig is given in Fig. 7. These findings indicate that reactance is not a significant factor for the current and voltage magnitudes used in this experiment.

3.3. Experiment 3

An oscilloscope current trace recorded for a typical live pig is illustrated in Fig. 8(a) and showed that there was a non-linear relationship between the rise in voltage and the corresponding increase in current. This was even more apparent when the leading edge was expanded [Fig. 8(b)]. The data from the profiles of six pigs were analysed and the average impedance plotted as a function of the applied voltage (Fig. 9). The upper curve shows the decrease in impedance with the increasing voltage from 0 to 350 volts, whilst the lower, almost straight line shows the impedance remains almost constant with the reduction in voltage, back to zero volts.

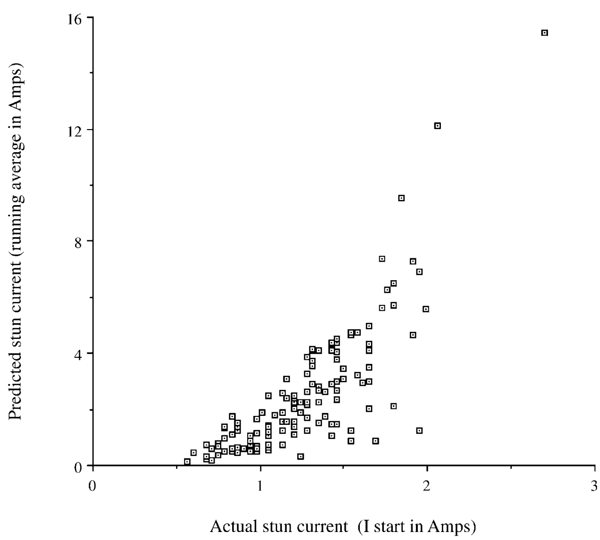

Fig. 5. Experiment 2: predicted stun current (running average) vs actual stun current (I start).

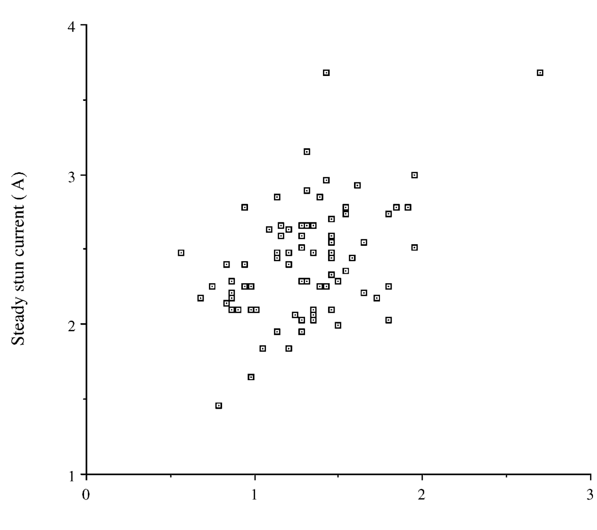

Fig. 6. Experiment 2: actual stun current (I start) vs steady stun current.

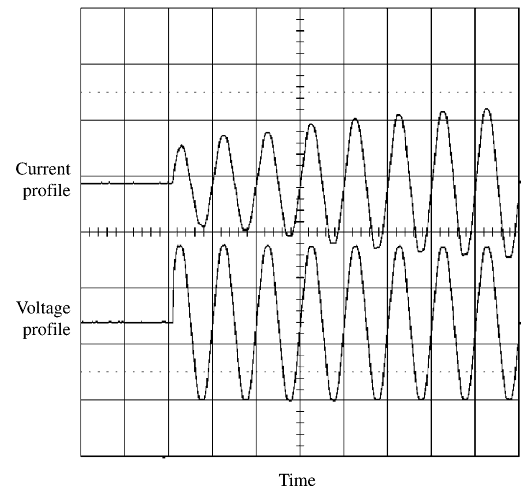

Fig. 7. Experiment 2: the leading edge of the current and voltage waveforms showing no significant phase change.

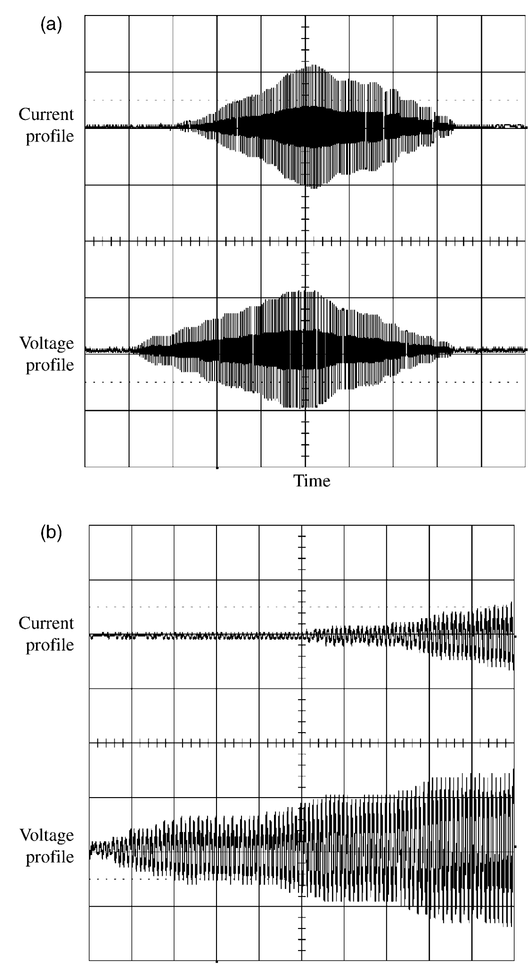

Fig. 8. (a) Experiment 3: the effect of voltage magnitude on the current profile from an anaesthetised pig; (b) experiment 3 the expanded current and voltage profiles from (a).

3.4. Experiment 4

Fig. 10 shows how the impedance of a typical pig's head changes with time post mortem using 300 volt application at 50 Hz a.c. sinewave for 2 s. The breakdown of impedance by the applied voltage occurred quickly in both the live pig and within the first 5 h post mortem but, after more than 22 h, the rate of impedance breakdown was noticeably reduced and the overall impedance to current flow was visibly higher.

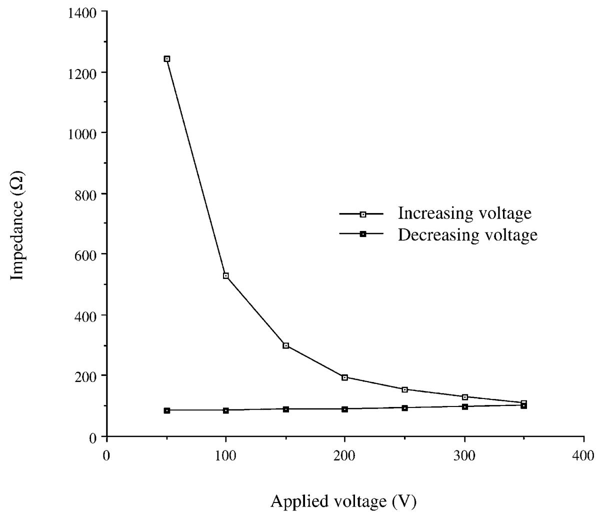

Fig. 9. Experiment 3: average impedance vs applied voltage.

4. Discussion

It was concluded from the results of experiment 1 that either the sensitivity of the SAS was insufficient or, there was only a poor correlation between the sensed impedance and subsequent stun current flow.

The correlation coefficient (0.80) obtained using bench-test equipment in experiment 2 was an improvement on the previous SAS measurements. However, the correlation was considered too low to meet the legislative requirements. Furthermore, a comparison of the predicted stun current with the steady current obtained when the current profile had reached a plateau showed a lower correlation than with the initial current measurement. This suggested that there was an additional contributing factor to overall impedance, which the simple application of Ohm's law did not explain it. In the past, this difference was attributed to impedance caused by tissue reactance (inductance and capacitance). However, if reactance is prominent, a phase-angle change would

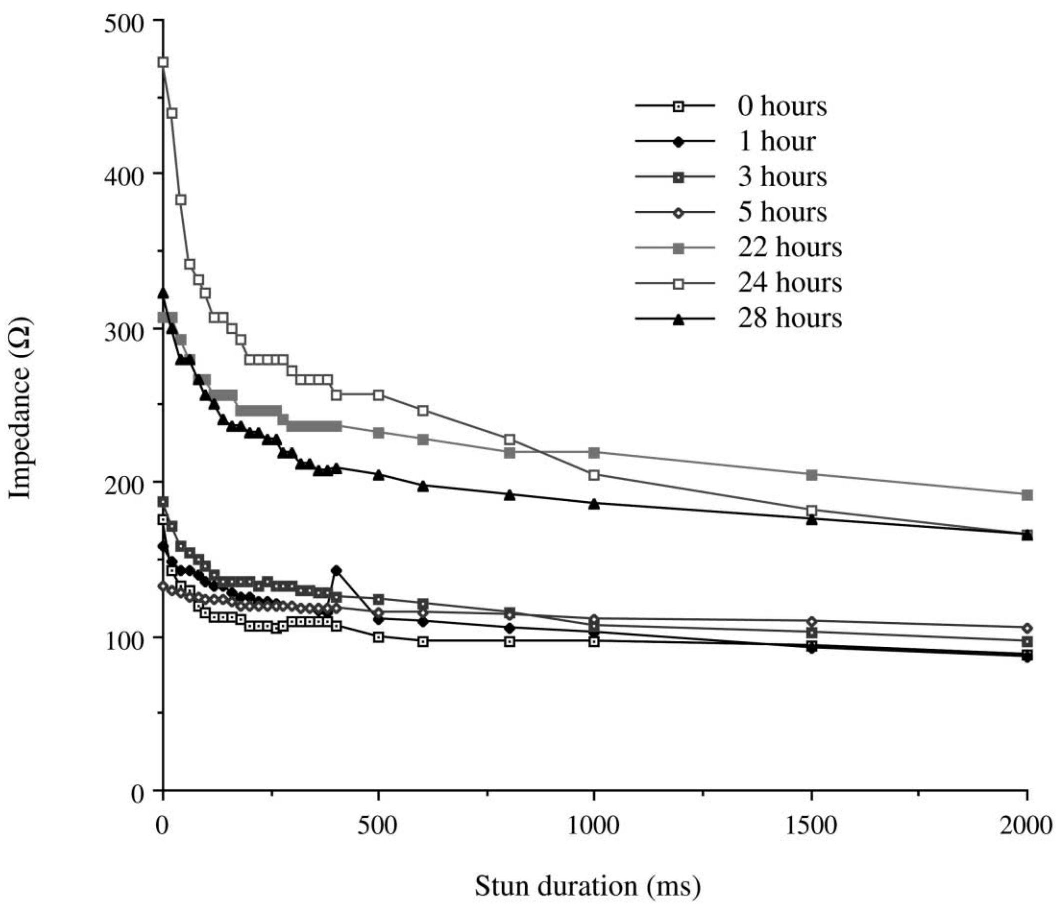

Fig. 10. Experiment 4: the effect of post mortem ageing on impedance.

be expected between the voltage and current waveforms. This was not apparent with the live pigs stunned during these experiments. The differences shown between the current profiles obtained with live and dead pigs' heads suggest that the additional contributing factor to overall impedance was lost at some time following the death of the animal.

The major difference between the sensed impedance and the stunning impedance was the magnitude of the voltage applied (25 volts d.c. to measure the impedance and 300 volts a.c. to stun). This suggested an effect of voltage magnitude on the impedance to current flow when applied to live pigs and the results from experiment 3 clearly demonstrated this. The overall hysteresis-loop (Fig. 8) produced suggests that the applied voltage in some way breaks down the impedance to current flow and this 'break down' remains when the voltage magnitude is reduced back to zero. Following the break down in impedance by high voltage application the relationship between current and voltage would appear to more closely match that expected from the application of Ohm's law. The results obtained with anaesthetised pigs demonstrated a significant effect of voltage magnitude on the impedance between the tong electrodes during stunning. This impedance profile was altered within 24 h of the death of the pig when the impedance of the dead pig's head more closely approaches that of a resistor. However, the results from experiment 4 showed that the change in response between live and dead pigs did not take place immediately. Therefore, a recently killed (<2 h post mortem) pig could be used as a model in future trials investigating the effect of stunning voltage on impedance to current flow.

5. Conclusions

The concept of a fail-safe device (Wotton & Whittington, 1994) relies on the ability of a low voltage current to measure accurately the impedance of an animal's head and thus to predict the stunning current when the stunning voltage is applied. The results of these experiments demonstrate that a low sensing voltage cannot be used to predict the impedance of a live pig's head for a given stunning voltage. Therefore a fail-safe device based on this principle is unlikely to fulfil the requirements of Council Directive 93/119/EC.

Acknowledgements

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