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<thead>
<tr>
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<td>Q1</td>
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<td>Q5</td>
<td>Please check and provide the department name (if any) for author ['Jeff A. Lines'].</td>
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<td>Q7</td>
<td>Please confirm the change of Ekman (1964) to Ekman and others (1964) in text citation as per reference list.</td>
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<tr>
<td>Q8</td>
<td>stimulus strength ranking indicator (SSRI)”. We have retained this abbreviation and expansion as is, and have taken “stimulus strength ranking index” as is. Please confirm.</td>
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| Q9              | Equation 3. Please clarify the need to show both the expansion as well as the abbreviation, in this equation “stimulus strength ranking indicator (SSRI)”.
| Q10             | Please provide the editor(s) name(s) and page range in reference Lindsay (2005). |

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PLEASE RESPOND WITHIN 48 HOURS
A wide range of electronic dog training collars (e-collars) is available in the UK, but information enabling purchasers to compare the important characteristics of these collars is not available. In this research, the electrical characteristics of 13 e-collar models were examined, and an approach to ranking the strength of the electrical stimuli was developed. To achieve this, the electrical impedance of dogs’ necks were measured so that e-collars could be tested under realistic conditions. This impedance was found to be about 10 kΩ for wet dogs and 640 kΩ for dry dogs. Two replicates of eight e-collar models and single copies of a further five models were then examined. The stimuli generated by these collars comprised sequences of short high-voltage pulses. There were large differences between e-collar models in the energy, peak voltage, number of pulses and duration of the pulses, but little variation between the replicates. The peak voltage varied with the impedance, from 6000V at an impedance of 500 kΩ to 100V at 5 kΩ. The highest voltages were generated for a few millionths of a second. Stimulus energy levels at the maximum strength setting with a 50 kΩ load ranged from 3.3 mJ to 287 mJ. A stimulus strength ranking index was then developed to enable the strengths of e-collars with diverse electrical characteristics to be ranked. This ranking shows a wide range in the stimulus strengths of collars, and that the relationships between ‘momentary’ and ‘continuous’ stimuli for various models differ significantly.
collar. Electrical impedance has two components, an in-phase (resistive) component and an out-of-phase (inductive or capacitive) component. When presented with a high resistive impedance, such as 1 MΩ, some collars generate peak voltages in excess of 6kV, while with an impedance of 500 kΩ the same collar may generate a peak voltage of only 20V. Despite the importance of impedance for the electrical output of e-collars, it does not appear to have been directly measured. Klein (2000, 2006) estimated resistance of dogs based on measurements of pig and human skin. He concluded that a dry dog was likely to present a resistance greater than 80 kΩ, while an expert witness in an Australian court case expected this value to be in the order of 100 kΩ (NAIA 2012).

In this investigation, direct measurements of the impedance of the dogs’ necks were made. Since biological materials seldom have linear impedance characteristics, the measurements were made under voltage conditions similar to those which occur with e-collars. A commercial electronic collar was modified for the purpose. In its unmodified state it delivered a ‘momentary’ stimulus comprising eight short voltage pulses in quick succession. Each pulse lasted 1 ms, and the interval between the pulses was 10 ms. This collar was altered to allow only one of these voltage pulses to be delivered, and to enable both voltage and current to be measured. Tests on human volunteers indicated that this modification significantly reduced the perceived strength of the stimulus to a level where it was not considered painful. They also showed that when the pulse sequence was not interrupted there was no significant variation in electrical impedance of the skin between the first and subsequent pulses. This approach enabled impedance to be measured on dogs at representative voltages without administering a full electrical stimulus. Technical details of the measurement and analysis method are given in Appendix 1.

The electrical impedances of 27 dogs were measured. The measurements were approved by the relevant institutional ethical review panels, and discussed in detail with the local Home Office Inspector who was satisfied that it did not require a project licence under the Animals (Scientific Procedures) Act 1956. All the dogs were privately owned and were volunteered by their owners who gave informed consent and, in most cases, interacted with their dogs during the measurement session. Inclusion criteria for the trial included that the dogs had a known background history, were over six months old, readily played or interacted with people, were not nervous, fearful or aggressive and had not been trained with e-collars. These conditions were to help safeguard the dog’s welfare. The dogs comprised four spaniels, 10 labradors and other retrievers, seven terriers, two German shepherd dogs, and four other dogs of working breed. Their sex, status, age, hair length, body condition, neck circumference and height were measured. Where possible, six single-pulse stimuli were applied to each dog: three when the coat was dry and three when it was wet. To provide distraction from the potentially perceptible stimulus, dogs were enticed to play or otherwise interact with their owner or a researcher while the single-pulse stimuli were applied (Notermans 1986, Kleber and Harper 1999). After every single-pulse stimulus, an assessment was made as to whether there had been any behavioural response from the dog which might indicate discomfort or pain. If any such responses were noted by the project team or owner then the sessions with that dog were stopped.

Sixty-four useable measurements were made on the 27 dry dogs, and 53 measurements were made on 22 wet dogs. In the majority of cases, the dogs did not react when the single-pulse stimulus was applied. Where they did react, their responses were limited to ear or eye movement, momentary attention redirection, and in one case both licking of lips and reluctance to re-engage in play. While these behaviours may have been a reaction to the single-pulse stimulus, the stimulus was also always preceded by a tone, and some dogs showed similar reactions (except lip licking) to the tone alone. In the dog which exhibited lip licking and reluctance to re-engage in play, the sessions were discontinued, in all other instances, sessions were continued by agreement of all present. The number of measurements collected is lower than the number of stimuli applied, since stimuli were continued to select the measurement range of the equipment. There are fewer wet measurements than dry measurements because the dry measurements were made first and some dogs lost interest in play or interaction during the test session. This was taken as a sign of disinterest rather than pain, fear or distress, as it did not occur immediately after the single-pulse stimulus was applied.

The results indicated that the impedance of the dogs could be described as a simple resistive load without a significant capacitive or inductive component. The distribution of values was highly skewed, so median values and percentiles were identified rather than mean values. For dry dogs, the median impedance was 640 kΩ, and the 90th and 90th percentile values were 22 kΩ and 950 kΩ, respectively. For the wet dogs, the median value was 10 kΩ, and the 10th and 90th percentile values were 4 kΩ and 150 kΩ, respectively. For some dogs, there was little variation between the replicate measurements, while others resulted in very different values. The median ratio of lowest to highest measured resistance was 1.3 and 1.7 for dry and wet dogs, respectively. This variation was probably due to changes in the contact area and amount of hair between the probes and the skin that occurred as the dog played. Similar changes are likely to occur when a collar is in normal use.

The high impedance presented by dry dogs was probably due to the properties of dog hair, the air gaps between the hairs, the layer of grease covering the skin and the high resistance of dry epidermal skin layers. The finding that resistance was lower in wet dogs is consistent with Klein (2006) and Lindsay (2005) as well as human data (IEC 2005). It was likely to be due to improved electrical conduction through wet hair using water pathways, and larger area of contact with the skin due to conduction of the electricity through the surface moisture on the skin surface.

Because of the variation between successive measurements and the small number of replicates, it was not possible to determine whether the resistance of individual dogs differed significantly. No significant trends between resistance and any of the measured factors, such as dog size, neck circumference or hair length and could be identified.

Electronic properties of collars

Thirteen different e-collar models from nine brands were examined. For eight of these models, two examples were examined, and for the remainder, only one. Seventeen of the collars were new and four were borrowed from dog trainers. Collars were bought anonymously and duplicate collars were bought from different suppliers. All collars were available to purchasers in the UK, and all except one were bought via the internet. The collars included the two best selling models manufactured by Electronic Collar Manufacturers Association (ECMA) members as used in 2007. ECMA is a self-regulatory industry body which sets publicly available standards to which its members’ products should adhere. Selection of most of the remaining models was based on information obtained from e-collar users participating in a related study (Blackwell and others 2012). One e-collar was selected outside these criteria because of its unusually large number of strength settings.

Each e-collar model was assigned an identity code. Collars E1 to E4 were brands from ECMA members, while N1 to N5 were brands from non-ECMA members. Where more than one model from a brand was examined, they were identified as ‘a’ and ‘b’ (eg, E1a and E1b represent two different models from the same brand). After purchase, collar N5 was found to be a counterfeit. It was included in the assessment as it may be attractive to consumers due to its low price. Collar E1a was donated to Defra some years before this research and is no longer available for purchase. Collar N4 was bought in the UK from a supplier based in the USA.

The voltage time histories generated by these collars were measured while they were loaded with resistive impedances of 500 kΩ, 50 kΩ, 5 kΩ and 0.5 kΩ. The upper three of these resistances were selected to represent the range of resistances likely to be found when the collars are in use. The lowest resistance was included because it is the resistance used for output current measurement tests by ECMA members (ECMA 2008). Almost all the collars offered the user at least eight different stimulus strength levels. Measurements were made with the e-collars adjusted to give maximum stimulus, the minimum stimulus and the value closest to the middle of the range. The repeatability,
of each collar was estimated by making at least 10 repeat measurements while it was set at the mid-range stimulus value and loaded with a 50 kΩ resistance.

The measurements showed that all the collars changed the voltage generated in response to electrical impedance of the dog and that the number, duration, frequency and voltage of the impulses varied widely between collar models. The ‘momentary’ stimulus comprised a short sequence of identical short but relatively high voltage impulses (Table 1). The ‘continuous’ stimulus comprised a much longer sequence of the same voltage pulses. Stimulus strength adjustment was mostly made by changing the peak voltage of the impulses, however, some collars also changed the number of voltage impulses used. Table 1 summarises some of these characteristics.

Table 1 shows the maximum voltages recorded for each e-collar model. Where more than one duration or number of pulses is given, the value increases as the strength of the stimulus is increased on the remote handset.

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Table 1: Description of collars tested. Collars are identified as ‘E’ or ‘N’ for ECMA/non-ECMA members, respectively.

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<table>
<thead>
<tr>
<th>Model Identity</th>
<th>Condition</th>
<th>Number of collars tested</th>
<th>Number of stimulus levels available</th>
<th>Number of voltage pulses in momentary stimulus</th>
<th>Duration of momentary stimulus (ms)</th>
<th>Voltage pulses per second in continuous stimulus</th>
<th>Maximum duration of continuous stimulus (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>New</td>
<td>2</td>
<td>16</td>
<td>2</td>
<td>12</td>
<td>285</td>
<td>8</td>
</tr>
<tr>
<td>N2a</td>
<td>New</td>
<td>2</td>
<td>64</td>
<td>272</td>
<td>420</td>
<td>514</td>
<td>10</td>
</tr>
<tr>
<td>N2b</td>
<td>Used</td>
<td>1</td>
<td>4</td>
<td>131</td>
<td>131</td>
<td>473</td>
<td>10</td>
</tr>
<tr>
<td>N3</td>
<td>New</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>80</td>
<td>90</td>
<td>11</td>
</tr>
<tr>
<td>N4</td>
<td>New</td>
<td>1</td>
<td>10</td>
<td>6</td>
<td>16</td>
<td>21/110</td>
<td>8.5</td>
</tr>
<tr>
<td>N5</td>
<td>New</td>
<td>2</td>
<td>1</td>
<td>n/a</td>
<td>n/a</td>
<td>10</td>
<td>&gt;60</td>
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<tr>
<td>E1a</td>
<td>New</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>120</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>E1b</td>
<td>New</td>
<td>2</td>
<td>8</td>
<td>n/a</td>
<td>n/a</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>E2</td>
<td>New</td>
<td>2</td>
<td>9</td>
<td>120</td>
<td>120</td>
<td>1000</td>
<td>11</td>
</tr>
<tr>
<td>E3a</td>
<td>New</td>
<td>2</td>
<td>127</td>
<td>4</td>
<td>10 or 20</td>
<td>80/119/255</td>
<td>12</td>
</tr>
<tr>
<td>E3b</td>
<td>Used</td>
<td>1</td>
<td>127</td>
<td>4</td>
<td>18</td>
<td>70/84/133</td>
<td>13</td>
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<tr>
<td>E4a</td>
<td>New</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td>73</td>
<td>7</td>
</tr>
<tr>
<td>E4b</td>
<td>Used</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td>57</td>
<td>7</td>
</tr>
</tbody>
</table>

*Note: N5 was tested for 60 seconds; it is presumed there is no cut-out.

Table 2 shows the maximum voltages recorded for each e-collar set to maximum stimulus strength and with various resistive loads from 500 kΩ to 0.5 kΩ. The bottom line of the table shows T_m, the duration in microseconds (µs) for which the voltage in one voltage pulse exceeds 50% of the maximum voltage. This duration was measured using the 500 kΩ load and maximum stimulus level.

### Table 2: Maximum voltages (V) recorded with collars set to maximum stimulus strength and with various resistive loads from 500 kΩ to 0.5 kΩ.

<table>
<thead>
<tr>
<th>N1</th>
<th>N2a</th>
<th>N2b</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>E1a</th>
<th>E1b</th>
<th>E2</th>
<th>E3a</th>
<th>E3b</th>
<th>E4a</th>
<th>E4b</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 kΩ</td>
<td>4116</td>
<td>3569</td>
<td>2856</td>
<td>2491</td>
<td>5490</td>
<td>7350</td>
<td>4754</td>
<td>4864</td>
<td>950</td>
<td>5757</td>
<td>3888</td>
<td>4990</td>
</tr>
<tr>
<td>50 kΩ</td>
<td>1450</td>
<td>2210</td>
<td>2330</td>
<td>2150</td>
<td>1730</td>
<td>4026</td>
<td>692</td>
<td>786</td>
<td>430</td>
<td>1300</td>
<td>910</td>
<td>966</td>
</tr>
<tr>
<td>5 kΩ</td>
<td>154</td>
<td>379</td>
<td>480</td>
<td>700</td>
<td>169</td>
<td>732</td>
<td>129</td>
<td>105</td>
<td>99</td>
<td>186</td>
<td>95</td>
<td>104</td>
</tr>
<tr>
<td>0.5 kΩ</td>
<td>24</td>
<td>45</td>
<td>17</td>
<td>93</td>
<td>26</td>
<td>80</td>
<td>17</td>
<td>15</td>
<td>12</td>
<td>20</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>T_m</td>
<td>15</td>
<td>13</td>
<td>14</td>
<td>12</td>
<td>32</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>39</td>
<td>23</td>
<td>24</td>
<td>20</td>
</tr>
</tbody>
</table>
strength then this would indicate that stimulus strength is relatively constant regardless of whether a dog is wet or dry.

Most of the e-collars were able to deliver both a ‘momentary’ and a ‘continuous’ stimulus. It is of interest to compare the strength of these two stimuli since either may be used at any time. Table 3 indicates the ratios of the energy delivered per second by a ‘continuous’ stimulus to that delivered by one ‘momentary’ stimulus. This shows that for a given dog and stimulus strength setting, a ‘continuous’ stimulus will deliver in one second between two and 143 times the electrical energy of a ‘momentary’ stimulus depending on the model of e-collar. This indicates that swapping between ‘momentary’ and ‘continuous’ stimuli has a much greater impact of a dog with some collars than with others.

Most of the e-collars were purchased in duplicate, to allow a limited assessment of individual variation of collar properties. The mean difference between the maximum voltages and between the energy outputs for the replicated e-collars was less than 10 per cent. To assess repeatability of the stimuli of each collar, at least 10 measurements were made of the energy dissipated into a 50 Ω load with the collar set to deliver a mid-level stimulus. The sd of the energy dissipated was on average only 2.5 per cent of the mean energy dissipated.

Reliability was not examined directly, however, faults were observed in two of the new e-collars. In one case, this resulted in a maximum strength impulse being delivered regardless of the level chosen via the dial. This occurred intermittently and appeared to be related to the direction of the force which was exerted on the dial during stimulus strength adjustment. This indicated a significant design fault since not only should the components be appropriately robust, but the electronics should also have been designed to prevent such inadvertent high stimulus levels. In another e-collar, the stimulus strength adjustment dial could be set to a value between the allocated levels. When this occurred, the resulting stimulus was substantially lower than that produced when set to either of the adjacent levels.

Development of a stimulus strength ranking method

Given their basic physiological similarities, it seems reasonable that short stimuli, such as those provided by electronic training collars will be ranked (but not rated) similarly by human beings and dogs. Human tests were therefore used to identify a ranking index to facilitate comparisons of e-collars and comparisons between modes of operation. No attempt was made to determine what electrical stimuli are perceptible or noxious to dogs.

The detection and pain thresholds of electrical stimulation have been shown to vary greatly between human subjects. Rollman and Harris (1967) reported that under closely controlled resistance conditions, the electrical current required to reach either the detection threshold, the pain threshold or the tolerance threshold varied by a factor of at least eight. This corresponds to a factor of 64 in energy. Slightly smaller ratios were reported by Laitinen and Eriksson (1985). Melzack and Wall (1965) suggested that these interpersonal differences were related to impedance, sensory, motivational and cognitive factors, habituation and sensitisation. Duker and others (2004) found that sensitisation to an electrical stimulus may occur at stimulus intervals of a few minutes, but that over a longer period the effectiveness of the electric stimulus decreased. Within a subject, the perception of electrical stimuli is likely to vary with physical factors, including the pathway of the current, the number and/or the frequency of the pulses, the total exposure time, the voltage and the current (IEC 2005).

With contact resistance maintained constant, Ekman and others (1964) showed that single 0.5-second exposures to a 50 Hz alternating current stimulus of varying voltage resulted in a perceived intensity that correlated closely with the square of the current (and hence energy). Rollman and Harris (1967) also controlled the contact impedance and showed that if the voltage of a stimulus was varied then the rating of pain was almost proportional to the square of the current although there was some variation between subjects (median power index 1.75, inter quartile range 1.24–2.58). However, Tursky and Watson (1964) showed that when electrode contact impedance changes, the perceived stimulus strength varies in a way which is not consistent with the use of either current or energy as an indicator of stimulus intensity.

Reanalysis of data presented by Notermans (1966) provides some information about the effect of short, repeated, voltage pulses of the type used in electronic training collars. Rapid sequences between 1 and 24, 5ms pulses were applied to human subjects, and the current in these pulses was adjusted so that each sequence resulted in the same subjective stimulus strength. Analysis of this data indicates that the square of the current multiplied by the number of pulses raised to the power 0.6 remained constant. Notermans (1966) also found that for short impulses of 0.15 ms to 15 ms, the perceived pain increased at a rate slightly lower than the increase in impulse duration. This increase is not necessarily valid for longer exposure times. Price and Tursky (1975) found that increasing exposure period from one second to 2.5 seconds did not result in significant change in the perception of a stimulus.

Under conditions of constant resistance (R), voltage and current are proportional to each other, so dissipated energy E (in Joules) can be calculated as

\[ E = P \int V(t)R^{-1} dt = P \int I(t)R dt \]  

(1)

where \( P \) is the number of voltage pulse repetitions, \( V(t) \) is the voltage which may vary with time, \( I(t) \) is the current and \( R \) the resistance.

In order to assess stimulus strength, the literature cited above suggests: firstly that the use of \( V^2 \) or \( I^2 \) in this equation is correct, but that the factor \( P \) should be raised to the power of 0.6; second, that a linear integration of time is not correct; and third, that the resistance \( R \) has a complex relationship with perceived stimulus strength and so must be held constant.

A short trial was conducted to assess whether these research findings might be relevant for the human perception of the relative strength of the stimuli produced by electronic training collars. Two male and two female members of the research team gave voluntary, informed consent for this study. They were exposed to pairs of stimuli at varying stimulus levels, and were required to identify which of the two stimuli was the strongest. The electrical stimuli were applied to the dorsal surface of the subjects’ forearms. This location was selected because preliminary investigations indicated that both the impedance and the stimulus perception were relatively independent of the location of the contact points in this region. The devices were moved slightly between each stimulus to avoid potential sensitisation.

Using the same procedure as had been used to assess electrical impedance of dogs, the electrical impedance of the dorsal surface of...
the forearm was measured on the first (male) subject. This was found to be in the range 35–50 kΩ. The stimuli used in this part of the study were generated by four e-collar models: E2, E3a, E4a and N2a. These collars were selected firstly to achieve a spread of stimulus types, and second to ensure that in this impedance range the dissipated energy was relatively constant and its ranking between collars did not vary. In this way, even if the exact impedance presented during tests did vary a little, the consequent variation in the energy output should be small.

The subjects were exposed to a ‘momentary’ stimulus from one collar and then immediately afterwards to a comparison ‘momentary’ stimulus from another e-collar. The order of testing was randomised between subjects. The subjects identified which of the stimuli in the pair felt stronger. Strengths settings on the four collars were varied to generate 16 stimuli that ranged in peak voltage from 138V to 680V, and in the number of impulses from two to 136. A total of 146 comparisons were made in a random presentation to control for order effects. Differences could be felt between the stimuli caused by the various collars with some feeling ‘sharp’, rather like a pin prick, and others more like a short cramp. However, regardless of these qualitative differences, it remained relatively easy to judge which stimulus was stronger.

The results of the comparison trials were used to generate a ranking of the stimuli used. Since the rankings provided by the four subjects were very similar, the individual comparison results were pooled to identify a single optimal ranking. This perceived strength ranking was then compared with the electrical properties of the devices derived from bench-testing using 39 kΩ resistive impedance.

The results (Fig 2), show that where the number of pulses was similar, the perceived stimulus strength increased with energy, but that where the number of voltage pulses varied, dissipated energy was a poor indicator of stimulus strength ranking. The Pearson correlation between the energy and the subjective rank was 0.72. Stimuli from N2a and E2 were perceived to be considerably less strong than the energy would indicate. These two devices delivered stimuli comprising 136 and 120 pulses, respectively, while E3a and E4a delivered stimuli comprising six or less pulses. In response to this observation, the energy calculation (1) was replaced by the more general relationship:

$$\text{Ranking indicator } = \int \text{V(t)} \, \text{dt}$$  \hspace{1cm} (2)

The resistance $R$ has also been removed from the calculation since measurements were made at a constant resistance. The calculation is, therefore, specific for a particular value of $R$.

The best fit for the data using this relationship is obtained using values $x=0.6$ and $y=2$. This is shown in Fig 3. The Pearsons correlation between the rankings of subjective stimulus strength and this ranking indicator was 0.98.

In order to be comparable, SSRI values must be calculated at the same resistance. Stimulus strengths would be ranked following the ranking of the SSRI values. It must be emphasised, however, that the results presented are based on a small sample of human subjects and collar stimuli, and would benefit from validation in a larger population using a wider range of stimuli. We do not know how far this algorithm is applicable outside the parameter range of the trials.

**Ranking of electronic training collar stimuli**

SSRI values were calculated for each collar at maximum and mid-range setting strength with a ‘momentary’ stimulus and one second of the ‘continuous’ stimulus (Fig 4). Calculations are based on the e-collar measurements made using an impedance of 50 kΩ. It is assumed that stimulus strength ranking calculation remains valid for stimuli lasting up to one second.

Fig 4 suggests considerable variation in the electronic training collar stimulus strengths. For e-collars, like the E2, N2b and N2a, the mid-range strength setting of the ‘momentary’ stimulus exceeds the maximum strength available on some other collars. Another difference between the e-collars is the relationship between the ‘momentary’ and ‘continuous’ stimulus. For six of the 10 e-collar types, this comparison could be made, the predicted strength of a one-second ‘continuous’ pulse with the collar at its mid-level setting exceeds the most powerful ‘momentary’ stimulus that the e-collar is capable of generating. For the remaining four e-collars, the predicted strengths of these two settings are more similar. If the difference in stimulus strengths between ‘momentary’ and ‘continuous’ is as large as indicated here, then some warning in the operation manual regarding this difference would seem to be prudent.
Discussion

A dog’s good training aid should produce repeatable stimuli and be reliable, easy to use correctly and difficult to misuse. E-collar industry information states that the primary purpose of e-collar stimuli is to attract the attention of a dog rather than to punish it. It is therefore important to be able to reliably and rapidly identify a suitable stimulus strength for a particular dog and then to apply it consistently regardless of the variations in the resistance that will occur as it moves or gets wet. The two types of stimulus, ‘continuous’ and ‘momentary’ should also be of a similar strength without adjustment of the handset. The range of stimulus strengths available should not significantly exceed that required to compensate for the range of sensitivities of individual dogs and as a result of differing levels of activity and motivation. Ideally, stimulus strength information identified for a dog using one collar model should be transferable to another collar model.

While the electronic characteristics of an e-collar are undoubtedly important, this alone will not be enough to determine its impact on dog welfare. This also depends on how the e-collar is used.

This investigation indicates that, generally, e-collars produced stimuli with little energy difference from pulse to pulse when the resistance remains constant, and with energy levels that remain similar over large changes in resistance. It is not clear, however, whether this results in a constant stimulus strength since the resistance presented by the dog has been shown to change significantly from application to application of the stimulus, and to change by more than an order of magnitude when the dog becomes wet. Human sensitivity research has shown a poor correlation between stimulus perception and energy, current or voltage when the resistance changes. There are various possible changes in the current path that could result in changes in resistance, and each may have a different effect on the perception of the stimulus strength. An investigation into this variation and its effect on stimulus perception under e-collar conditions would therefore be valuable.

Human perception of electrical stimulus strength has been shown to vary so that, with resistance held constant, a 64-fold change in energy can result in similar strength assessments by different subjects (Rollman and Harris 1967). There is good reason, therefore, to expect considerable differences in the perception of electric stimulus strength between individual dogs. The e-collars tested were all adjustable in stimulus strength. The median for all the collar models tested, of the maximum to minimum energy ratio, was 81. However, the range was from 3 to 1112. This suggests that there may be less adjustment than is ideal on some collars, and more than is necessary in others.

The peak voltages delivered by e-collars can be very high, particularly when the resistance between the probes is high. However, the highest voltages are present for only a few milliseconds of a second, and much of this voltage is dissipated across hair, fat and dead skin layers that are not innervated. Peak voltage alone does not indicate the power of the device, and on its own is not an obvious welfare concern.

E-collar models have large differences in stimulus characteristics, such as the number, frequency and duration of pulses and the electrical energy dissipated. This makes comparison of different collar models, comparison of ‘momentary’ and ‘continuous’ stimuli strengths and the transfer of settings known to be suitable for a dog from one collar to another impossible without further information. The small-scale investigation of stimulus strength ranking resulted in a method which was consistent with previous research and resulted in a good ranking of the perceived strength of electrical stimuli on human skin. The SSRI developed from this information may facilitate comparison of different e-collars, however, it should be used cautiously until validated in a larger test. The method has potential to enable the outputs of collars to be compared and ranked. It suggests that stimulus strength of the collars that use a large number of voltage pulses is overestimated by the dissipated energy metric.

Energy tests used by industry representatives stipulate that collars should be tested to identify the maximum energy they deliver over an impedance range from 0.5 kΩ to 100 kΩ (ECMA 2008). This seems a reasonable test range, although this study suggests that a range from 4 kΩ to 100 kΩ would be more relevant. These tests should perhaps be replaced by SSRI calculations over the same range. The ECMA’s ‘fixed output current test’ is specified for 0.5 kΩ. Since this impedance is an order of magnitude lower than that measured in dogs, it has little relevance.

A cut-out function, limiting the time for which a ‘continuous’ stimulus can be applied is important because it provides some protection against both poor collar use and accidental collar activation. All the collars except for e-collar N5 had such a function, however, in one of these the limit was described in the manual as eight seconds, whereas tests showed it to be 11 seconds. Although reliability was not assessed systematically in this study, two faults were found in the new e-collars, one of which could result in an unexpected application of the highest stimulus level. A test to search out faults under conditions that may be encountered in the field should be part of a welfare-oriented e-collar quality assurance scheme.

During this investigation, contact between the research team and both sides of the dog collar debate was avoided as much as possible in order to protect the independence of the work. The only significant piece of information requested of the industry was an identification of the most frequently sold collars. This information was used in our selection of collars to be investigated. However, the lack of contact with the industry means that we are not aware of what unpublished information about dog characteristics is held and used by the industry. However, since the resources were not available to properly validate any such information, the use of such information could have compromised the integrity of this investigation.

Conclusions

E-collars of the same model produce repeatable stimuli, with little difference from pulse to pulse, and little difference from collar to collar. However, different e-collar models have large differences in their stimulus characteristics. It cannot be assumed that a given strength setting provides a similar stimulus when moving between collar models or brands. Similarly, the relationship in strength of ‘momentary’ and ‘continuous’ stimulus varies widely between collars.

The peak voltages delivered by e-collars vary significantly with the resistance of the dog and can be very high. However, the highest voltages are present for only a few microseconds, and do not indicate an obvious welfare concern.
The impedance of a dog varies from stimulus to stimulus. It also depends significantly on whether the dog is wet or dry. E-collars generally deliver stimuli of similar energy when the impedance is varied, however, it is not known whether the perceived stimulus strength remains constant. The effect on stimulus strength of these variations should be investigated and, if necessary, methods to improve consistency explored.

Human beings vary significantly in their sensitivity to electrical stimuli, we may therefore expect individual dogs to exhibit significant variation. The available adjustment of stimulus strength on some e-collar models may be too small to properly accommodate this variation, and on other e-collar models it seems to be excessive.

Objective information about the electrical stimuli differences is not available at the point of purchase—and is not accessible without the use of sophisticated measuring equipment. Further information on collar characteristics should be made available. The implicit assumption of the industry is that the strength of the electrical stimulus is related to the dissipated energy. This appears to be an oversimplified assumption which does not enable collars to be properly compared.

Further development and validation of the SSRI scoring algorithm is recommended since this approach may be useful for characterising and comparing collars, and for comparing different modes of operation of collars.

Faults were found in the design of two of the 13 e-collar models tested, which resulted in an unexpected change in the stimulus delivered. A more robust examination of collar design is therefore recommended.

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