JOURNAL OF FORENSIC SCIENCES

J Forensic Sci, January 2011, Vol. 56, No. S1
doi: 10.1111/j.1556-4029.2010.01580.x
Available online at: onlinelibrary.wiley.com

PAPER

PATHOLOGY/BIOLOGY

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Muscle Contraction During Electro-muscular Incapacitation: A Comparison Between Square-wave Pulses and the TASER® X26 Electronic Control Device*

ABSTRACT: Electronic control devices (including the Advanced TASER® X26 model produced by TASER International) incapacitate individuals by causing muscle contractions. To provide information relevant to development of future potential devices, effects of monophasic square waves with different parameters were compared with those of the X26 electronic control device, using two animal models (frogs and swine). Pulse power, electrical pulse charge, pulse duration, and pulse repetition frequency affected muscle contraction. There was no difference in the charge required, between the square waveform and the X26 waveform, to cause approximately the same muscle-contraction response (in terms of the strength-duration curve). Thus, on the basis of these initial studies, the detailed shape of a waveform may not be important in terms of generating electro-muscular incapacitation. More detailed studies, however, may be required to thoroughly test all potential waveforms to be considered for future use in ECDs.

KEYWORDS: forensic science, *Sus scrofa*, TASER, muscle contraction, *Rana pipiens,* electromuscular incapacitation, electronic control devices

TASER® electronic control devices (ECDs) (alternatively referred to as "electro-muscular disruption devices," "electro-muscular incapacitating devices," or "conducted electronic weapons") are used by law-enforcement personnel to incapacitate individuals quickly and effectively, without causing lethality. Incapacitation results from muscle contractions generated by electric pulses from the device. In a laboratory study, TASER International's Advanced TASER M26 ECD (Scottsdale, AZ) was the only device (out of five models evaluated) to effectively incapacitate conscious swine that were exposed (1). TASER International's latest model for law-enforcement personnel is the Advanced TASER X26 ECD.

In terms of muscular contraction effectiveness (amount of force generated along a net-force vector), peak values of force generated by the leg muscles of anesthetized swine exposed to X26 devices (2–5) and to a private-citizen version of an ECD (known as the "C2" [6])[†] were slightly higher than values in previous studies of M26-device applications (7,8). These values were generally between 200 and 300 N on any given limb of an animal.

An adequate amount of muscle contraction results in effective incapacitation of a subject by preventing voluntary actions. The U.S. Marine Corps defines "incapacitation" as "either physical inability (real or perceived) or mental disinclination to resist or pose a threat to friendly forces" (9, pp 11). Other investigators have determined the commercially available law-enforcement ECD used in this study (X26 device) is effective (10). TASER ECDs operate at a much lower pulse rate than would cause full tetanus (therefore resulting in less potential muscle damage [11] or other sequelae [12,13]). Jauchem et al. (2) showed a graph of muscle contractions resulting from applications of the TASER X26 device, illustrating the lack of full tetanus in swine.

The significance of the shape of the waveform in causing nerve excitation and muscular contraction is largely unknown. In physical therapy, muscular stimulation is used to increase muscle tone, especially after an injury. Some investigators (e.g., [14]) have shown waveform shape makes little difference in comfort levels during muscular stimulation. Bennie et al. (15) suggested sine wave stimulation might produce equivalent muscle tension (in human quadriceps) with a lower mean stimulation current than biphasic square waves. Based on work by Reilly (16), however, monophasic square waves may be just as effective as more complex waveforms and

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*This work was supported by the Joint Non-Lethal Weapons Program, Marine Corps Base, Quantico, Virginia. The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of Defense position, policy, or decision. This research complied with the Animal Welfare Act and adhered to the principles enunciated in the Guide for the Care and Use of the Laboratory Animals per SECNAVINST 3800.38B and AFMAN 40-401(I). The authors have not had any relationship with any manufacturers of electronic control devices, including employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding. Research was supported by US Navy Contract #N001408WR20088.

Received 25 Aug. 2009; and in revised form 3 Dec. 2009; accepted 19 Dec. 2009.

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may be more energy efficient as the charge is not repeated in an opposite phase.

We investigated effects of different waveform parameters (including pulse power, electrical pulse charge, pulse duration, and pulse repetition frequency) in frogs and swine as animal models to evaluate the effectiveness of and to facilitate the improved design of ECDs similar to the TASER X26 ECD. Muscle-contraction results were compared to the effect caused by the X26 device, allowing us to generate strength-duration curves showing the threshold response (at the same level of stimulation as the X26 ECD) as a function of the duration of the stimulating pulse.

Materials and Methods

Animal Models

This series of experiments used frogs (*Rana pipiens*) and swine (*Sus scrofa domestica*). The frog muscle preparation is a classical model for studying muscle physiology. We used the results of an initial pilot study series of frogs to determine details of pulses we used in a subsequent series of swine experiments.

The reasons for selecting the *Sus scrofa* pig model included its similarities to humans in terms of chemical and physical characteristics of blood, respiratory parameters, and responses to muscular exercise (17).

All experiments and animal care procedures were approved by the Institutional Animal Care and Use Committee of Air Force Research Laboratory, Brooks City-Base, Texas, and were conducted according to the U.S. National Institutes of Health's "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources—National Research Council.

Methods: Frogs

Earlier presentations included the general methods regarding anesthesia, isolation of gastrocnemius muscles, delivery of waveform energy, acquisition of waveform and muscle-contraction response, and euthanasia (18). The present series used four frogs weighing (mean ± SEM) 37.2 ± 1.9 g. Gastrocnemius muscles were isolated by severing the femur (proximal to the knee), the tibia (distal to the knee), and the Achilles tendon. The isolated gastrocnemius muscles weighed 1.40 ± 0.01 g and were 36.6 ± 0.3 mm in length.

Muscle preparations were stimulated using an arbitrary waveform generator (model 33250A; Agilent Technologies, Santa Clara, CA). Two waveforms were used: ramping-up and ramping-down of multiple durations ($N = 4$ animals). All pulse durations were between 10 μsec and 10 msec. When necessary, an inverting, solid-state amplifier (model E103; Comlinear Corporation, Fort Collins, CO) voltage increased the voltage to as much as 13 V. As this was an inverting amplifier, negative-polarity waveforms were used so the tissue perceived the inverse voltages.

Based on thresholds required for muscle contraction because of ramping-up and ramping-down waveforms, duration curves were developed for voltage, current, charge, power, and energy.

Methods: Swine

Eight male Yorkshire swine weighing from 51.0 to 59.2 kg were electrically stimulated to determine strength-duration thresholds according to pulse charges. The animals were anesthetized initially with Telazol® (6.0 mg/kg IM) and maintained with propofol (100–125 μg/kg/min IV or to anesthetic effect) (PropoFlo®; Abbott Laboratories, North Chicago, IL).

Details of other methods have been described earlier (2) to include the animal positioning with one minor alteration. Instead of attaching 5-lb weights to each limb, the transducer on each limb was tightened to a tension of 5 lb before the start of each experiment. The animal was positioned in a suspended sling in the supine position with each limb attached to an isometric force transducer (SSM AJ 150 force sensors; Interface Manufacturing, Scottsdale, AZ), which was calibrated to measure pull strength in lbs. The transducers were attached with nylon rope to a strap around the hock of each hind limb and around the cannon bone of each forelimb. They were positioned to record a positive force with a pull toward the center of the body.

Stimulations were elicited with the use of three different devices. For a baseline of comparison, a 5-sec burst from the TASER X26 ECD was used. Square-wave pulses from 10 μsec to 1 msec were produced by a system consisting of the following: (i) BRL model 4000 power supply (Life Technologies Inc., Gaithersburg, MD); (ii) 4-μF capacitor; and (iii) DEI PVM 4150 high-voltage switch (Directed Energy Inc., Fort Collins, CO). The voltage was limited to about 1500 V, and the power supply was capable of a 200-mA output. The 10-msec square-wave pulses were produced by a Grass S88 bench top stimulator (Grass Technologies, West Warwick, RI). Maximum voltage with this device was 150 V.

Two barbed electrodes, obtained from a TASER X26 cartridge, were placed in the skin of the animal to allow the stimulus to reach it. The first electrode was 7.6 cm left of the umbilicus, and the second was positioned 12.7 cm rostrally and 5.1 cm right of midline from the xiphoid process. Pulsers were connected to these barbs with alligator clips. The superior barb was connected as the "hot" lead, and the inferior lead was on the same side as ground.

Each square-wave exposure consisted of a burst of five pulses of the tested duration (10 μsec, 100 μsec, 1 msec, or 10 msec) at a repetition rate of 20 Hz. (Similarly, the X26 device operates at about 19 Hz. Graphic representations of the shape of the X26 waveform have been provided previously [3,8,19].) The monotonic increase in pull strength because of the five pulses was estimated to reach a maximal value comparable to the maximum pull strength of the 5-sec burst of the X26 device.

A series began with a 5-sec X26-device exposure followed by 10 successive exposures of square pulses at one of four different durations (with each exposure incrementally increasing in amplitude). This procedure was followed by another X26-device exposure and 10 more exposures of square pulses of different durations. This was repeated until all four durations were tested; then a final 5-sec exposure with the X26 device was performed. Each exposure was separated by 2 min of rest, and physiological data were recorded for 30 sec at the time of stimulation. A full testing series consisted of 45 exposures.

Voltage and current waveforms were collected using a TDS3504 oscilloscope and voltage probes P5100 and P5050 (Tektronix, Beaverton, OR). The voltage was measured at the source electrode, and the current was determined as the voltage before a 1-Ω carbon-film resistor in the return path to ground.

The last pulse of the exposure was captured as a representative voltage and current. Analysis of waveforms was performed using custom software that determined the pulse duration at 10% of the peak of the waveform, minimum and maximum voltage and current, the net charge (summation of positive and negative charges) after subtracting the baseline offset, peak power, and peak pulse energy. The peak-to-peak pull of each limb was recorded for each shot using a MP150 data acquisition system (Biopac Systems, Goleta, CA). All statistics were performed using R software (v2.5.1; R Foundation for Statistical Computing, Vienna, Austria). Thresholds were determined using probit analysis. This method allowed for the possibility of a dose-response estimate and ensured that the number of exposures on each animal was consistent. A pass–fail criteria were created which required the square pulse pull result to be 95% or greater than the pull result of the subsequent X26-device shot for each leg. As each animal responded with different forces, normalizing them to the X26 limb responses resulted in data within each subject being comparable.

Previous studies of intramuscular current during electrical stimulation have usually focused on individual muscles (e.g., [20]). During applications of ECDs, however, generally a wide range of muscle groups is affected. For this reason, during the studies of swine, we did not focus on any individual muscles, but rather on the total overall contraction force of each limb in a single direction.

Statistics

Statistical calculations were performed using R software (v2.5.1). All errors are expressed as standard errors unless otherwise stated. A result was considered significant at $p < 0.05$.

Results

Frog Data

Examples of 100-μsec ramping-up and ramping-down waveforms are shown in Fig. 1. (Shapes of 10-μsec, 10-msec, and 100-msec waveforms were similar.) The voltage-versus-duration, charge-versus-duration, and energy-versus-duration curves relating to these waveforms are shown in Fig. 2. There was little difference between pulse shapes designed to be opposite in transition times. When a one-sided, paired, *t*-test was performed for both pulse shapes at each pulse duration, there were generally no differences between pulse shapes in pulse voltage, peak charge, or peak energy per pulse. The exception was the 1.0-msec ramping-up pulse charge threshold, which was 22.6 nC larger. There was a significant difference in pulse voltage, charge, and energy for thresholds using the 10-msec pulse: The ramping-up pulse had higher thresholds than the ramping-down pulses by 260 mV, 425 nC, and 168 nJ.

Pulse transition times seemed to have little effect on the threshold of muscle-nerve activation at threshold levels when pulse durations were at and below 1 msec. Pulse transition time did become a significant factor in threshold levels for pulses 10 msec in duration.

For this reason, the subsequent series of whole-body swine experiments was designed to compare, more thoroughly, the effects of simple square-wave pulses versus pulses from the standard X26 ECD.

Swine Data

Based on results obtained from the frog experiments, subsequent experiments using the swine model were limited to testing selected monophasic square pulses from 10 μsec to 10 msec in duration and comparing these with the standard X26-ECD pulse. Examples of the waveform shapes of the square-wave and TASER X26 pulses are shown in Fig. 3.

The absolute force of muscle response for each limb to the X26 ECD was (mean ± SEM) 242 ± 10 N. As each animal exhibited different values, these were normalized for further analysis. To determine a charge strength-duration curve for the monophasic square pulse eliciting a response similar to the TASER X26 device, thresholds were determined by probit regression (calculated based on the criteria explained above in "Methods.")

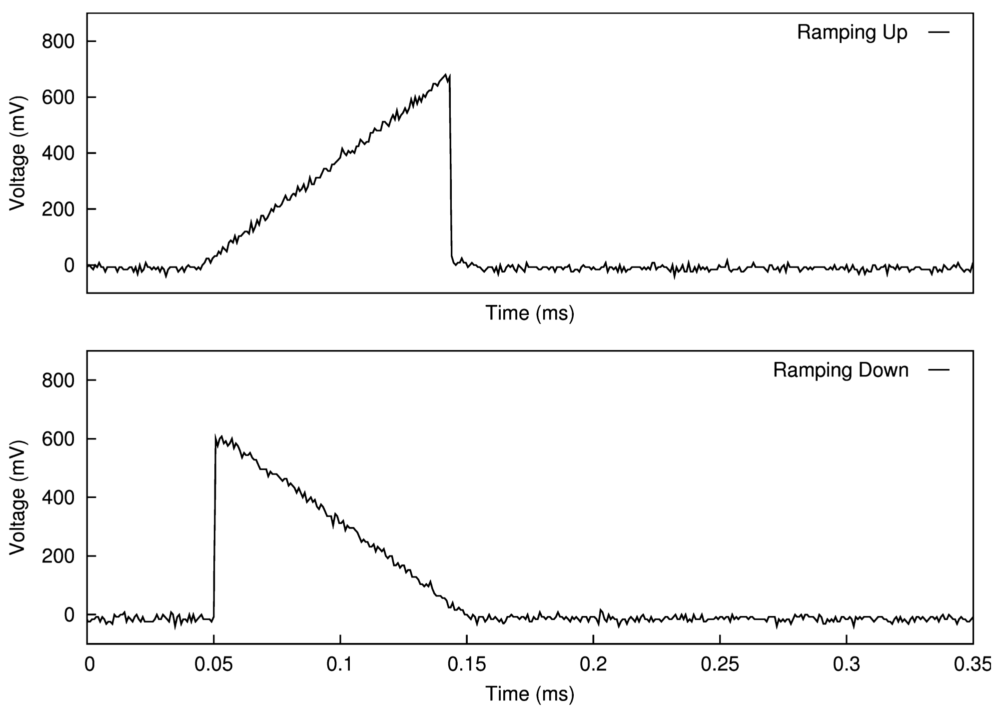

FIG. 1—*Example voltage waveforms of 100-μsec ramping-up and ramping-down pulses used on frog gastrocnemius muscles.*

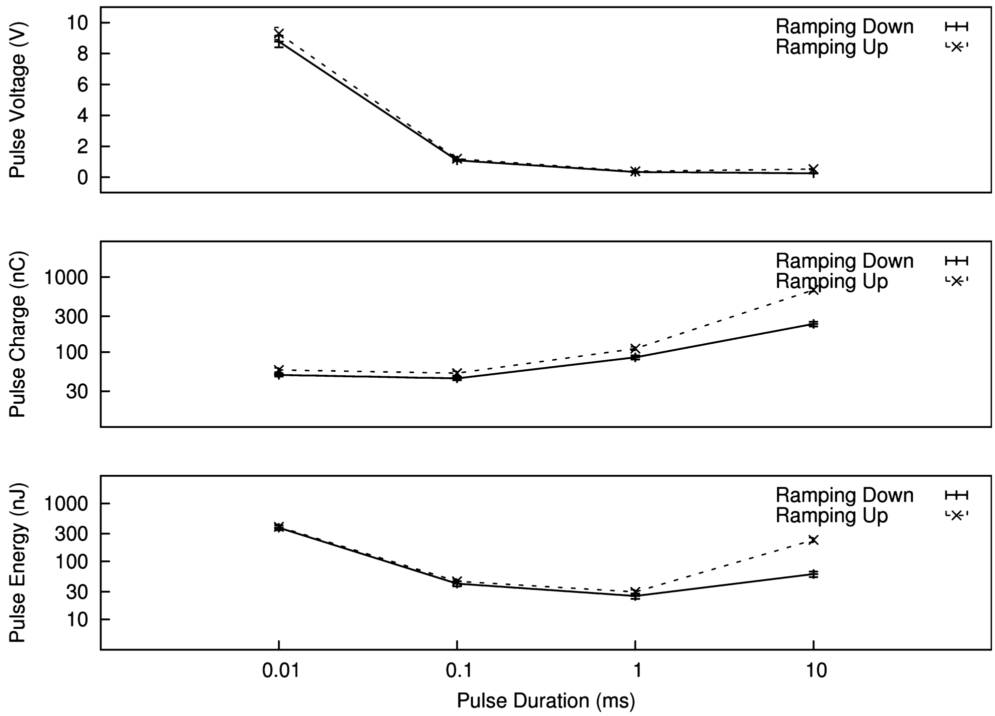

FIG. 2—*Strength-duration curves of voltage-versus-duration, charge-versus-duration, and energy-versus-duration at threshold using ramping-up and ramping-down triangular pulses to stimulate frog gastrocnemius muscles. Means ± standard errors are shown (*N = 4 *animals).*

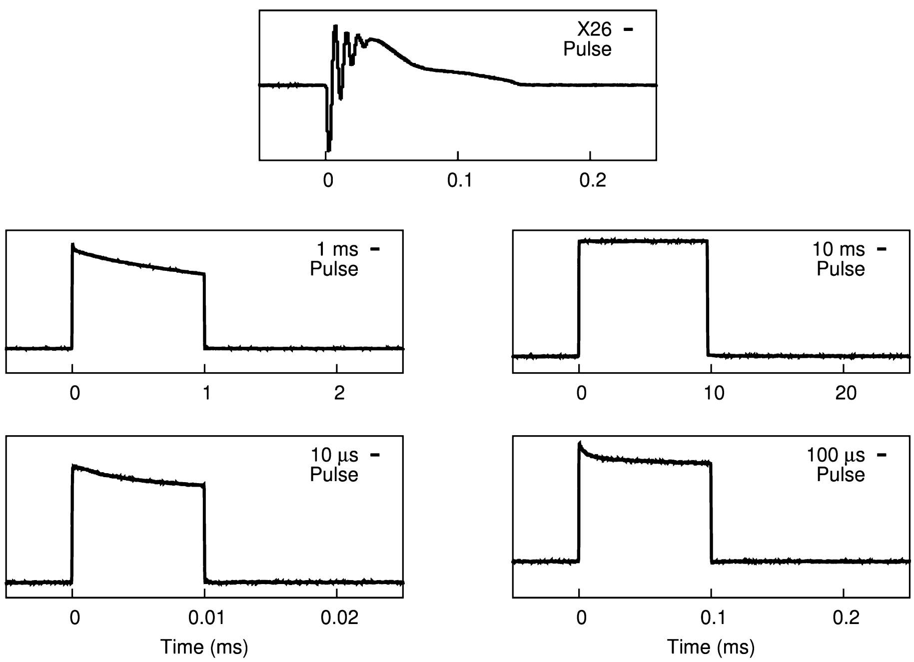

FIG. 3—*Examples of waveform shapes (time-versus-voltage plots) of the square-wave and TASER X26 pulses applied to swine.*

Strength-duration curves in Fig. 4 show values of pulse charge and pulse energy at threshold (average for all four limbs of the animals). The curves also show the net charge and energy in a single X26-device pulse, according to its duration. The X26-device point falls in line with the strength-duration curves for the monophasic square pulses.

Welch's two-sample *t*-test was calculated on charge and energy results. There was no significant difference between the charge eliciting similar muscle response to the X26 (66.9 ± 11.1 μC) and the 100-μsec square (52.9 ± 9.1 μC) pulses. There was also no significant difference noted between the energy of the 100 μsec (23.5 ± 4.7 mJ), 1 msec (38.3 ± 11.5 mJ), and the X26 (32.8 ± 6.2 mJ) pulses. The 10-msec pulse was significantly different from all other pulses in both charge and energy.

Threshold values based on individual subjects with the 10-μsec pulse, in both charge and energy, were too high to be calculated

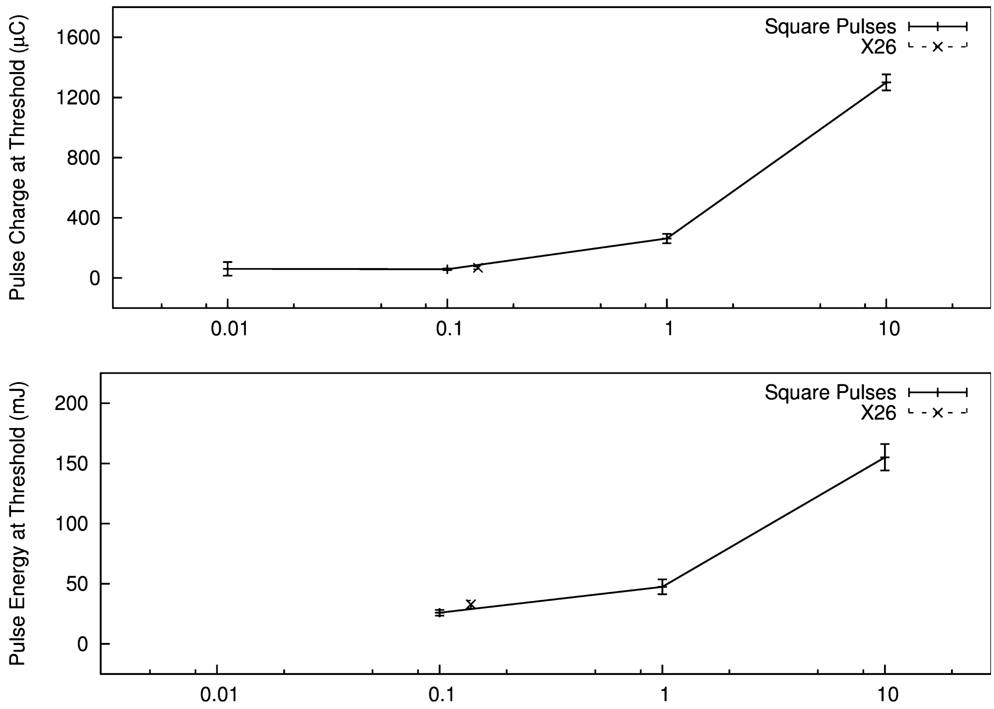

FIG. 4—*Peak pulse charge and energy at threshold for a burst of five 20-Hz square pulses to elicit a muscular response on swine similar to a response caused by a 5-sec TASER X26 stimulus on the same subject. Standard errors are shown.*

accurately. Additionally, because of variability, we were unable to calculate an accurate energy threshold using probit regression with the 10-μsec pulse duration when all tests were combined.

Discussion

The major difference between the monophasic square waveform and the X26 waveform is the multitude of transitions in the X26 waveform compared to the two in the monophasic square waveform. Testing of opposite ramping waveforms (the most extreme in transitions) for muscle excitation showed thresholds to be similar, in terms of charge and energy. This suggested the effect on threshold levels by transitions was minimal for pulses with durations under 1 msec.

It is also important to note that the *in vitro* method oversimplifies the effect the voltages may have on the entire body. Testing bursts of monophasic square pulses and bursts of X26-device waveforms on an *in vivo* model showed that the same amount of charge and energy per pulse was required for an equal level of stimulation delivered at the same electrodes. The 20-Hz, 5-sec pulse burst was a good comparison to the 5-sec TASER burst because it allowed the muscle forces generated to reach a maximum level that could be compared to the maximum level of the X26 burst stimulation (as shown in Fig. 4).

The shape of the X26 ECD is mostly monophasic, and the results closely fit the threshold curves created with square waves. As shown by the strength-duration curve, there was no difference in the pulse charge or energy required to cause the same response with the square waveform and the TASER X26-device waveform. Based on these findings, one may suggest square-wave stimulation does not represent an improvement over the existing X26 waveform, in terms of the threshold for muscle contraction in swine.

Other factors may contribute to the selection of an effective ECD wave shape. TASER International uses the wave shape of the X26 for the short high-amplitude peak at the onset of each pulse (21). It is used to arc over an air gap created when the dart does not make perfect contact with the target. (Elimination of such a "precursor" portion of the pulse does not appear to have a significant effect on peak muscle contraction caused by the device [19]). More detailed studies may be required to thoroughly test all potential waveforms to be considered for future use in ECDs. For example, it is unknown whether pulses opposite in polarity to those shown in this report would have similar effects.

Conclusion

The stimulation-response curves for bursts of monophasic square pulses and X26 pulses show that the level of energy and charge required to cause the same response was not different for similar pulse durations. Thus, based on these initial studies, the detailed shape of a waveform may not be as important in terms of generating electro-muscular incapacitation, as the pulse charge.

Conflict of interest: The authors have no relevant conflicts of interest to declare.

Acknowledgments

We thank David A. Fines, Advanced Information Engineering Services, San Antonio, for technical assistance and anesthesia maintenance during the experiments.

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