

Muscle contraction during electro-muscular incapacitation: A comparison between square-wave pulses and the TASER[®] X26 electronic control device.*

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Running header: TASER electronic control device

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

Introduction

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® M26¹ ECD, 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), peak values of force generated by the leg muscles of anesthetized swine exposed to X26 devices [2-4] were slightly higher than values in previous studies of M26-device applications [5-6].

An adequate amount of muscle contraction could result in effective incapacitation of a subject by preventing voluntary actions. The US Marine Corps defines “incapacitation” as “either physical inability (real or perceived) or mental disinclination to resist or pose a threat to friendly forces” [11]. Other investigators have determined the commercially-available electronic control device used in the present study (X26 device) is effective [12]. TASER® ECDs operate at a much lower pulse rate than would cause full tetanus (therefore resulting in less potential muscle damage) [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., ref. [7]) have shown waveform shape makes little difference in comfort levels during muscular stimulation. Bennie et al. [8] suggested sine wave stimulation may produce equivalent muscle tension (in human quadriceps) with a lower mean stimulation current than square waves. On the basis of work by Reilly [9], however, square waves may be just as effective as more complex waveforms.

¹ M26 and X26 are trademarks of TASER international, Inc. TASER® is a registered trademark of TASER International, Inc.

We investigated effects of different waveform parameters (including pulse power, net/gross 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 electronic control devices 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 same level of stimulation as the X26 ECD. The resulting comparisons suggest there is no difference in electrical pulse properties of the X26 and a monophasic square pulse for a similar muscle response.

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 [4].

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, USA, and were conducted according to the US 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 [10]. The present series used four frogs weighing (mean $\pm$ 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 (Agilent Technologies, Santa Clara, California, USA; model 33250A). Two waveforms were used: ramping up and ramping down of multiple durations ($N = 4$ animals). All pulse durations were between 10 μ s and 10 ms. When necessary, an inverting, solid-state amplifier (Comlinear Corporation, Fort Collins, Colorado, USA; model E103) voltage increased the voltage to as much as 13 V. Since this was an inverting amplifier, negative-polarity waveforms were used so the tissue perceived the inverse voltages.

Based on thresholds required for muscle contraction due to 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 – 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 (125 mg/kg/min/ IV). 100-125 μ g·kg⁻¹·min⁻¹ (or to anesthetic effect) of propofol (PropoFlo®, Abbott Laboratories, North Chicago, Illinois).

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, USA), which were 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 towards the center of the body.

Stimulations were elicited with the use of three different devices. For a baseline of comparison, a 5-s burst from the TASER®-X26 ECD was used. Square-wave pulses from 10 μ s to 1 ms were produced by a system consisting of the following: a) BRL model 4000 power supply

(Life Technologies Inc., Gaithersburg, MD, USA); b) 4 μ F capacitor; and c) DEI PVM 4150 high-voltage switch (Directed Energy Inc., Fort Collins, CO, USA). The voltage was limited to about 1500 V and the power supply was capable of a 200-mA output. The 10 ms square-wave pulses were produced by a Grass S88 bench top stimulator (Grass Technologies, West Warwick, RI, USA). 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.

Square-wave exposures consisted of five pulses at a repetition rate of 20 Hz. (The X26 device operates at about 20 Hz.) The additive value of pull strength due to the five pulses was estimated to reach a maximal value comparable to the 5-s burst of the X26 device.

A series began with an X26-device shot followed by ten successive shots of square pulses at one of four different durations (with each shot incrementally increasing in amplitude). This procedure was followed by another X26-device shot and ten more shots of square pulses of different durations. This was repeated until all four durations were tested; then a final 5-s shot with the X26 device was performed. Each shot was separated by two minutes of rest, and physiological data were recorded for 30 s in close proximity to the time of stimulation. A full testing series consisted of 45 shots.

Voltage and current waveforms were collected using a TDS3504 oscilloscope and voltage probes P5100 and P5050 (Tektronix, Beaverton OR, USA). 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 shot was captured as a representative voltage and current. Analysis of waveforms was performed using custom software which determined the pulse duration at 10% of the peak of the waveform, minimum and maximum voltage and current, the net charge 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, USA). All statistics were performed using R software (v2.5.1, R Foundation for

Statistical Computing, Vienna, Austria). Thresholds were determined using probit analysis. A pass-fail criteria was 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.

Previous studies of intramuscular current during electrical stimulation have usually focused on individual muscles (e.g., [14]). During applications of electronic control devices, 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, R Foundation for Statistical Computing, Vienna, Austria). 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- μ s ramping-up and ramping-down waveforms are shown in Fig. 1. (Shapes of 10- μ s, 10-ms, and 100-ms waveforms were similar.) The voltage-vs.-duration, charge-vs.-duration, and energy-vs.-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 ms 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 ms 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 ms. Pulse transition time did become a significant factor in threshold levels for pulses 10 ms 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 μ s to 10 ms in duration, and comparing these with the standard X26-ECD pulse.

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”).

Strength-duration curves in Fig. 3 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 ($66.9 \pm 11.1 \mu\text{C}$) and the 100 μ s square pulse ($52.9 \pm 9.1 \mu\text{C}$) pulses. There was also no significant difference noted between the energy of the 100 μ s ($23.5 \pm 4.7 \text{ mJ}$), 1 ms ($38.3 \pm 11.5 \text{ mJ}$) and the X26 ($32.8 \pm 6.2 \text{ mJ}$) pulses. The 10 ms pulse was significantly different from all other pulses in both charge and energy.

We were unable to calculate threshold values based on individual subjects with the 10 μ s pulse in both charge and energy. Additionally we were unable to calculate an accurate energy threshold using probit regression with the 10 μ s pulse duration when all tests were combined. These high errors were due to a voltage limitation of our sources at that pulse duration.

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 ms.

It is also understandable to note 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 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 pulse burst was a good comparison to the 5-s TASER® burst because it allowed the muscle forces generated to summate similarly with both pulse stimulations.

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.

Conclusion

The stimulation-response curves for bursts of monophasic square pulses and X26 pulses show 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. Other factors may contribute to the selection of an effective ECD wave shape. TASER® International claims to use the wave shape of the X26 for the short high-amplitude peak at the onset of each pulse [15]. It is used to arc over an air gap created when the dart does not make perfect contact with the target. More detailed studies may be required to thoroughly test all potential waveforms to be considered for future use in ECDs such as whether pulses opposite in polarity to those shown in this report would have similar effects.

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Figure Legends

Figure 1. Example voltage waveforms of 100 μ s ramping up and down pulses.

Figure 2. Voltage-vs-duration, charge-vs-duration, and energy-vs-duration curves of ramping-up and ramping-down triangular pulses. Means $\pm$ standard errors are shown (N = 4 animals).

Figure 3. Peak pulse charge and energy for 5, 20-Hz square pulses to elicit a muscular response similar to a response caused by a 5 s TASER® X26 stimulus. Standard errors shown.

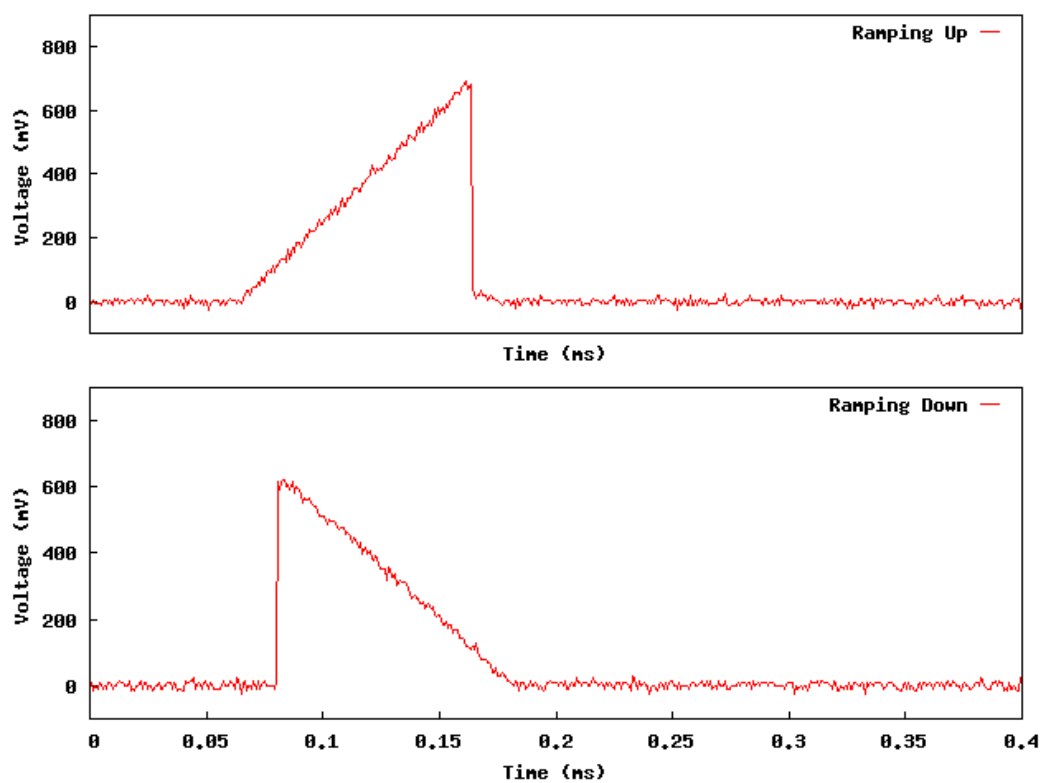


Figure 1

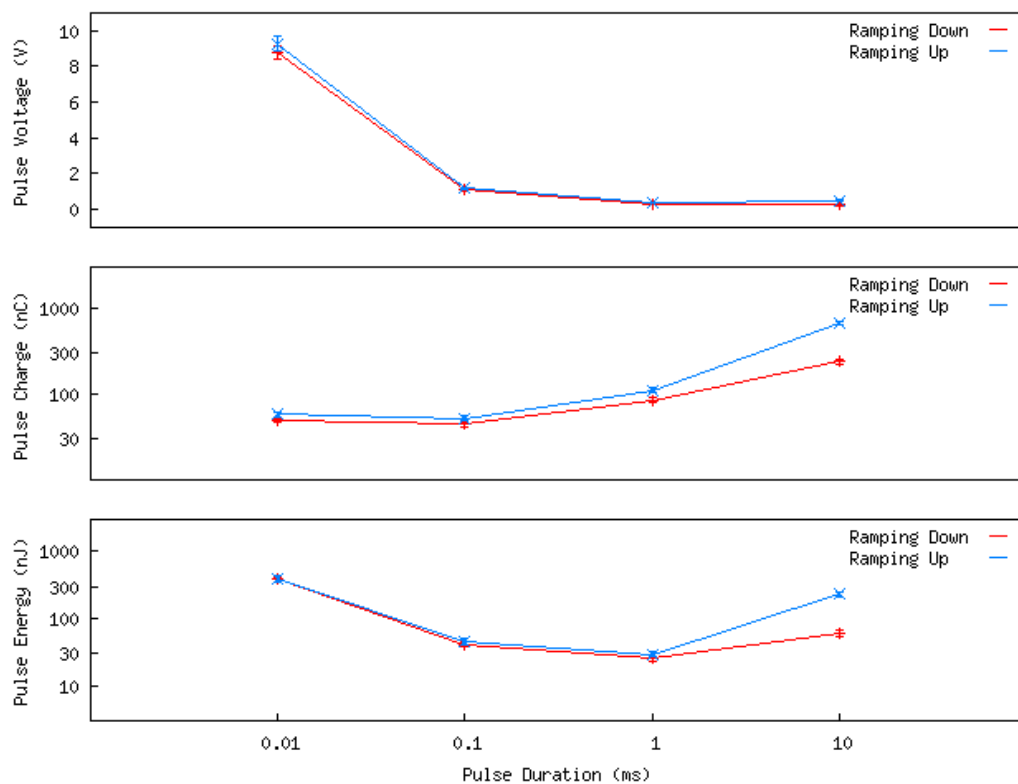


Figure 2

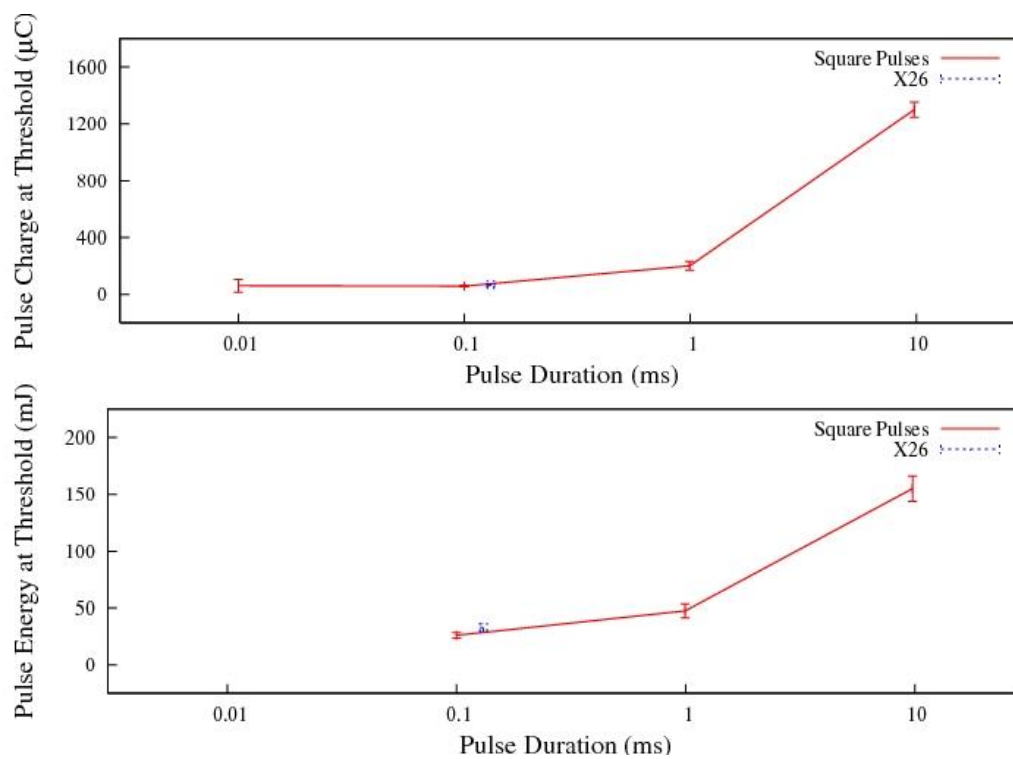


Figure 3