31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Theoretical Comparisons of Nerve and Muscle Activation By Neuromuscular Incapacitation Devices

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***Abstract*—In this study important aspects of the TASER® M26™ and X26™ neuromuscular incapacitation device waveforms are simulated, analyzed and contrasted against electrical stimulation with rectangular waveforms (commonly used in therapeutic stimulation devices). Expected skeletal muscle forces evoked by M26™ and X26™ stimulation are simulated also and compared against forces expected with higher or lower frequency trains. The first half-cycle of the M26™ damped 50 kHz sinusoidal wave is the main contributor to stimulation threshold with this device. The pseudo-monophasic component of the X26™ waveform primarily determines threshold for this system, with the leading damped 100 kHz component contributing little in this regard. Simulated isometric forces evoked at 19 Hz with either device are moderately intense (about 46% of maximal). Lower frequencies would likely not provide sufficient levels of contraction to override volitional motor control.**

I. Introduction

NEUROMUSCULAR incapacitation devices (NMIDs), also called conducted electrical weapons (CEWs), are designed to stimulate skeletal muscle contractions in the torso and extremities to a level that safely and temporarily incapacitates a subject. Two of the more widely adopted such devices, the TASER® M26™ and X26™ models [1], bear many similarities and some differences in design of their neuromuscular stimulation strategies to therapeutic medical devices which also employ transcutaneous stimulation (e.g. surface muscle stimulators for use in rehabilitation, or Functional Electrical Stimulation (FES) systems [2] for restoration of motor control in paralysis). In this paper, important aspects of the M26™ and X26™ waveforms and stimulus trains are analyzed and in addition contrasted against rectangular waveforms (which are more commonly used in therapeutic devices) with similar timing.

II. Methods

A. Waveform Simulations

The TASER® X26™ is designed to deliver a 5 second burst of stimuli through two tethered darts at 19 Hz. While the device generates initial arcing voltages of approximately 50,000 V, typical peak voltages delivered to a subject are approximately 1,200 V. The complex overall waveform of each stimulus has been modeled in this study through combination of an initial damped 100 kHz sinusoid (the arcing component) superimposed on a lower frequency, pseudo-monophasic component (of about 70 microseconds) derived from hyperbolic tangent terms. The net simulated waveform (Figure 1) well matches the experimental test waveform of the X26™ into typical test loads, and can then be varied and modulated readily in computer simulations. Similarly, the M26™ device delivers a stimulus waveform which has been modeled here as a damped 50 kHz sine wave of two cycles duration. Voltages delivered by the M26™ are about 3,000 to 5,000 V following arcing. The simulated M26™ stimulus waveform is seen in Figure 2.

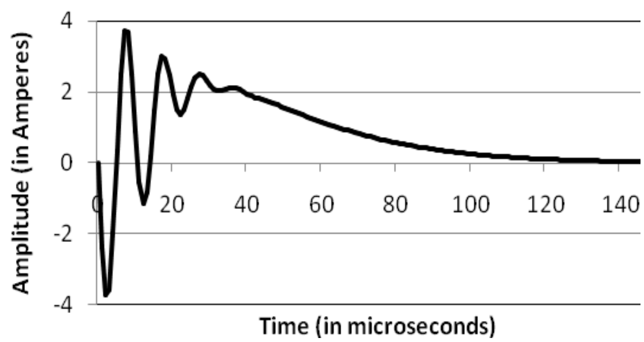

Fig. 1. The simulated TASER® X26™ stimulus waveform consists of an initial damped 100 kHz sinusoidal component superimposed upon a lower frequency pseudo-monophasic component modeled by rising and then falling hyperbolic tangent terms.

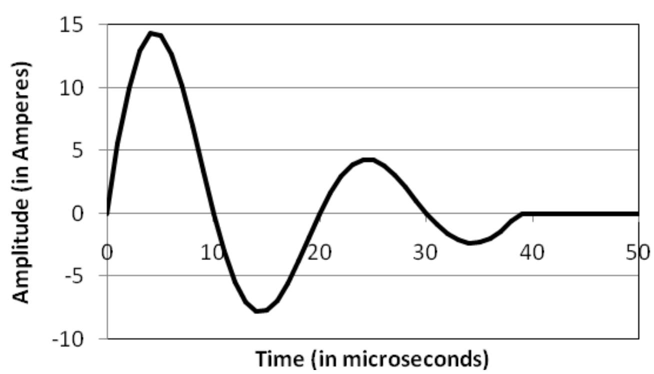

Fig. 2. The simulated TASER® M26™ stimulus waveform is made up of two complete cycles of a damped 50 kHz sine wave.

B. Excitation Threshold Simulations

X26™ and M26™ waveform threshold excitation of motor nerves has been simulated by applying the waveform

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models of Figure 1 and 2 to the mammalian, myelinated nerve model developed by McIntyre, Richardson, and Grill (MRG) [3] via 'ends stimulation'. Cathodic threshold excitation at the termination of a 21-node 10 micron diameter MRG compartmental cable coded in NEURON [4] has been used to simulate excitation at motor nerve terminations. Results have been normalized with respect to rheobase current levels for rectangular, cathodic stimuli (which are more commonly used with therapeutic, medical devices). Strength-duration results for X26™ and M26™ stimulation are also then compared to those for rectangular waveforms of similar timing.

Reilly and colleagues have also recently simulated strength-effect considerations for the X26™ and M26™ using his SENN model of nerve excitation [5]. He has also previously simulated [6] the dependence of nerve excitation threshold in general for brief applications of sinusoidal stimuli upon number of cycles (and half-cycles). We have modeled here the threshold behavior (again, for 'ends simulation' of MRG nerve) of the complex X26™ and M26™ waveforms in comparison to varying numbers of cycles (and half-cycles) of corresponding pure sinusoids (100 kHz for the X26™, and 50 kHz for the M26™).

C. Skeletal Muscle Force Recruitment Simulations

The 5 second, 19 Hz bursts of stimuli delivered by both the X26™ and M26™ devices are designed to elicit skeletal muscle contraction at moderately high force levels (just high enough to incapacitate against volitional effort to resist). We have used a skeletal muscle isometric force generation model developed by Ding and colleagues [7] to simulate the theoretical levels of force likely to be generated by these TASER® devices. This model, based upon parameters derived from electrical stimulation of human quadriceps, has been implemented here in MATLAB. Force levels have been predicted at the TASER® 19 Hz rate (as well as for trains at 1 Hz, 10 Hz, 38 Hz, and 57 Hz) as normalized to those for (maximal) 100 Hz stimulation. 38 Hz and 57 Hz are twice and three times the 19 Hz stimulation rate of the TASER® devices.

III. Results

Strength-duration simulation results for both X26™ and also for M26™ single stimulus, cathodic waveforms in comparison to cathodic monophasic, rectangular stimuli of similar duration can be seen in Figure 3. Also seen are predicted threshold levels for the X26™ waveform decomposed into the separate leading damped sinusoid component (as it would stimulate as a cathodic-first waveform) as well as the slower monophasic component. For comparison to the M26™ threshold, threshold for two cycles of an undamped pure 50 kHz sine wave are seen. These results confirm that threshold for the complete X26™ waveform is virtually the same (higher by 4%) as that for the pseudo-monophasic component of the X26™ waveform (separate from the leading damped sine component). Therefore, the leading damped sine component (which is designed primarily to contribute to arcing) contributes little to the overall stimulation effectiveness of the X26™ pulse. This conclusion is further confirmed via threshold charge calculations for the simulations of Figure 3. Charge threshold for the composite X26™ waveform (integration of charge within both the positive and negative components) is 17% higher than that for the corresponding 100 microsecond monophasic rectangular pulse. Charge threshold for the pseudo-monophasic component of the X26™ waveform is essentially the same as that for a 70 microsecond monophasic rectangular pulse. By comparison to stimulation by an undamped 50 kHz sine wave of two cycles duration, the M26™ waveform threshold is only 4% higher, indicating that the first half-cycle of both waveforms dominates the stimulation threshold behavior. The M26™ waveform, by comparison to the X26™, has a predicted current threshold level that is just over 6 times higher. This ratio is quite similar to that found by Reilly and colleagues [5] using his SENN model, where for M26™ and X26™ waveforms delivered into 400 Ω test loads, a ratio of threshold currents of 6.5 was found.

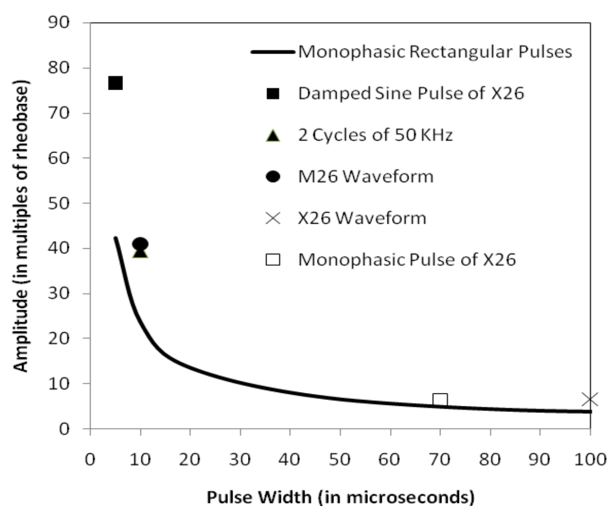

Fig. 3. Strength-duration predictions for X26™ and M26™ cathodic stimulation in comparison to equivalent cathodic, monophasic rectangular stimuli (results normalized to rheobase). Seen also are predictions for stimulation by the pseudo-monophasic component of the X26™ as separate from the leading damped 100 kHz sine pulse of the X26™ (which alone as a cathodic stimulus would have a much higher threshold); as well as threshold for 2 cycles of pure (undamped) 50 kHz stimulation.

Comparisons between X26™ and M26™ cathodic threshold behavior to varying numbers of cycles (and half-cycles) of comparable 100 kHz and 50 kHz stimulation are depicted in Figure 4. As expected, sine wave stimulation at both frequencies exhibits higher threshold predictions for full cycles (versus those on half-cycles). This comparison is particularly interesting for the M26™ waveform (a damped sinusoid) which is somewhat less than that predicted for only one cycle of the equivalent (undamped) 50 Khz waveform and modestly above predictions for equivalent (undamped) sine waves of three cycles or more.

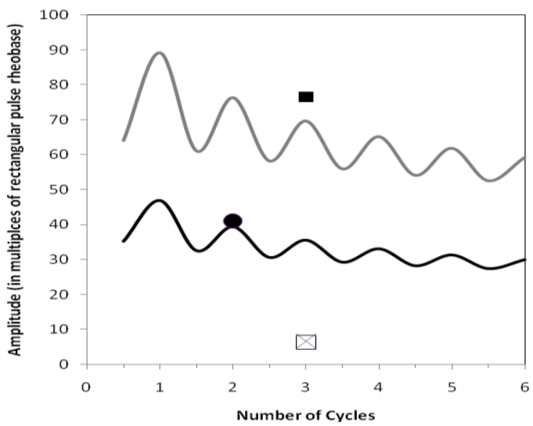

Fig. 4. Simulation results for cathodic X26™ and M26™ threshold stimulation in comparison to that for varying numbers of cycles (and half-cycles) for pure, undamped sinusoid waveforms at 100 kHz (top curve) and 50 kHz (bottom curve). Symbols for X26™, damped sine pulse of the X26™, and the pseudo-monophasic component of the X26™ are the same as in Fig. 3. All thresholds are depicted as multiples of the rheobase level for cathodic rectangular pulses.

Predicted isometric force responses for TASER® stimulation of motor nerves at 19 Hz are seen in Figure 5. The 19 Hz response is well fused at approximately 46% of the level produced by equivalent (maximal) 100 Hz stimulation. Anecdotally, it has been reported that stimulation rates much below 15 Hz may not sufficiently override volitional motor control. Predicted 10 Hz force levels here are not well fused and oscillate around a force generation level just above 20% of maximal. Predicted force generation levels at 38 Hz (twice the TASER® rates) and 57 Hz (three times TASER®) increase to 74% and 87% of maximal, respectively.

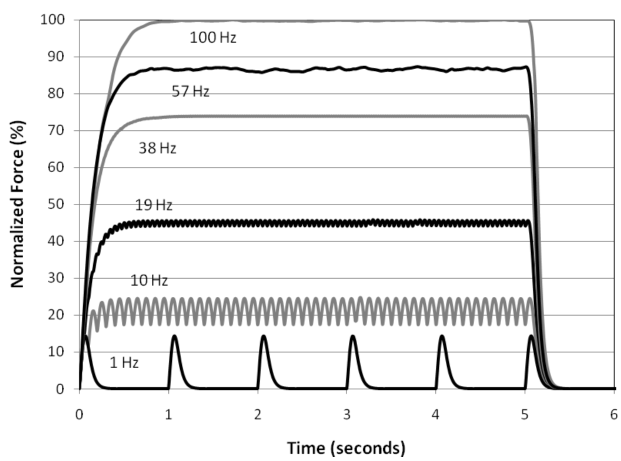

Fig. 5. Simulation results for isometric force responses to 5 second bursts at the TASER® 19 Hz rate as well as at 1, 10, 38 (twice the TASER® rate), 57 (three times TASER®), and 100 Hz. Forces are plotted against the peak (maximal) force evoked by the 100 Hz burst.

IV. Conclusions

This simulation study indicates that the first half-cycle of the **M26™** damped 50 kHz sinusoidal wave is the main contributor to achieving stimulation threshold with this device. The pseudo-monophasic component of the **X26™** waveform primarily determines threshold for this system, with the leading damped 100 kHz (arcing) component contributing little in this regard. Simulated isometric forces evoked at 19 Hz with either device are moderately intense (about 46% of maximal). Lower frequencies would likely not provide sufficient levels of contraction to override volitional motor control.

References

[1] M. W. Kroll and J. D. Ho (Eds.), "*TASER Conducted Electrical Weapons: Physiology, Pathology, and Law*," Springer, 2009.

[2] G. Venkatasubramanian, R. Jung, and J. D. Sweeney, "Functional Electrical Stimulation," in *Wiley Encyclopedia of Medical Devices and Instrumentation*, 2nd ed, J. Webster, Ed.: Wiley, 2006.

[3] C. C. McIntyre, A. G. Richardson, and W. M. Grill, "Modeling the excitability of mammalian nerve fibers: influence of afterpotentials on the recovery cycle," *J Neurophysiol,* vol. 87, pp. 995-1006, Feb 2002.

[4] N. T. Carnevale and M. L. Hines, *The NEURON book*. Cambridge ; New York: Cambridge University Press, 2006.

[5] J.P. Reilly, A.M. Diamant and J. Comeaux. "Dosimetry considerations for electrical stun devices," *Phy Med Biol*, vol. 54, pp. 1319-1335, 2009.

[6] J. P. Reilly, *Applied Bioelectricity: From Electrical Stimulation to Electrical Pathology*. New York: Springer, 1998.

[7] J. Ding, A. S. Wexler, and S. A. Binder-Macleod, "A predictive fatigue model--I: Predicting the effect of stimulation frequency and pattern on fatigue," *IEEE Trans Neural Syst Rehabil Eng,* vol. 10, pp. 48-58, Mar 2002.