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TECHNICAL NOTE

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Pulse Variations of a Conducted Energy Weapon (Similar to the TASER® X26 Device): Effects on Muscle Contraction and Threshold for Ventricular Fibrillation*

ABSTRACT: Conducted energy weapons (such as 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, a ''Modifiable Electronic Stimulator'' was used to evaluate the effects of changing various parameters of the stimulating pulse. Muscle contraction was affected by pulse power, net/gross charge, pulse duration, and pulse repetition frequency. The contraction force increased linearly as each of these factors was increased. Elimination of a precursor pulse from X26-like pulses did not have a significant effect on the normalized force measured. Muscle-contraction force increased as the spacing increased from 5 to 20 cm, with no further change in force above 20 cm of spacing. Therefore, it is suggested that any future developments of new conducted energy weapons should include placement of electrodes a minimum of 20 cm apart so that efficiency of the system is not degraded. In the current study, the 50% probability of fibrillation level of X26-like pulses ranged from 4 to 5 times higher than the X26 itself. Relatively large variations about the X26 operating level were found not to result in fibrillation or asystole. Therefore, it should be possible to design and build an X26-type device that operates efficiently at levels higher than the X26.

KEYWORDS: forensic science, *Sus scrofa,* TASER, conducted energy weapon, muscle contraction, electromuscular incapacitation, electronic control devices, fibrillation

TASER® conducted energy weapons (alternatively referred to as ''electronic control devices,'' ''electro-muscular disruption devices,'' or ''electro-muscular incapacitating devices'') are used by law-enforcement personnel to incapacitate individuals quickly and effectively. Incapacitation results from muscle contractions generated by electric pulses from the device. In a laboratory study, TASER International's Advanced TASER M26 device was the only device (out of five models that were evaluated) to effectively incapacitate conscious swine that were exposed (1). TASER International's latest model for law-enforcement personnel is the Advanced TASER X26 device (M26 and X26 are trademarks of TASER International, Inc. TASER® is a registered trademark of TASER International, Inc.).

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The initial portion of the X26 device waveform (the ''arc phase'' [2]) is a very high-voltage short-duration pulse designed to penetrate clothing. It serves as a low-impedance electrical conductor that directs a second phase of the waveform of the X26 device into the body. Effects of the initial phase on overall muscle contraction are unknown.

To evaluate the effectiveness of and to facilitate the improved design of conducted energy weapons that may be similar to the X26 device, we investigated effects of an in-house-designed and -constructed ''Modifiable Electronic Stimulator'' (MES). Modifiable parameters included pulse power, pulse shape, net/gross charge, pulse duration, and pulse repetition frequency. The applied pulse was similar in shape to that of the X26. Our study included measurements of the effects of varying electrode spacing on muscle contraction during exposure to the X26. We also investigated effects of absence of the precursor pulse, repetition rate, and power. In order to evaluate the effective operating margin of potential future devices, we increased the power of the MES until ventricular fibrillation was achieved.

Materials and Methods

Animal Model

The *Sus scrofa* pig model was selected for several reasons, including similarities to humans in terms of chemical and physical characteristics of blood, respiratory parameters, and responses to muscular exercise (3,4). Ten domestic swine (*Sus scrofa domestica*), mean weight of 53.7 kg (range 49.9–60.8 kg) were used for these studies.

Anesthesia and Set-up

Details of the techniques of animal preparation, anesthesia, and physiological measurements, have been presented previously (3,4). Animals were anesthetized with an intramuscular injection of tiletamine HCl and zolazepam HCl (Telazol®, 6 mg/kg). The opioid buprenorphine (0.005–0.2 mg/kg) was administered to facilitate placement of an endotracheal tube. Anesthesia was maintained with 100–125 μg/kg/min (or to anesthetic effect) of propofol (Propo-Flo®; Abbott Laboratories, North Chicago, IL).

Compared with other anesthetic regimens, total intravenous anesthesia with propofol is less likely to cause cardiovascular (5) or pulmonary (6) dysfunction, and less decrease in arterial or mixed venous oxygen partial pressure (7), in swine. Inhalation anesthetics such as halothane may not have been appropriate for these studies, since muscle-cell damage (as indicated by increased creatine phosphokinase) can result from such use (8). Depth of anesthesia was verified by nasal septum pinch, coronary band hoof pressure, and jaw tone. Absence of both reflexes and lack of jaw tone were taken to indicate the animal was at a suitable anesthesia plane.

The MES was upgraded from an original system (9), to allow the simulation of a greater number of waveforms. It is a small low-to-moderate energy repetitively pulsed electric pulse generator that will allow pulse amplitude, pulse duration, and pulse repetition rate to be varied. The MES may be configured to deliver either a single pulse or a series of pulses at an adjustable repetition rate. A thyratron is used to precisely control the repetition rate, which was set at 19 Hz (except in the study of changing pulse repetition rate, listed below).

The MES produces a selectable pulse shape of an LRC (inductance/resistance/capacitance)-type exponentially decaying bipolar pulse, an RC (resistor/capacitor) monopolar pulse, or a combination of the two. The LRC waveform was not used by itself in this experiment. The two types of pulses may be added or subtracted. Subtracting one pulse from the other results in a pulse similar in character to the Advanced TASER X26 (i.e., with the precursor).

A comparison of the MES and the X26 into identical loads is shown in Fig. 1. The intent of the design of the MES was not to replicate exactly pulses of the X26, but rather to approximately match the first positive and negative swings in current. The major differences between the two are: (a) the quicker extinguishing of the initial sinusoidal ring for the MES, (b) the RC discharge amplitude not reaching as high a level in the MES as the X26, and (c) a slightly higher and longer tail to the discharge.

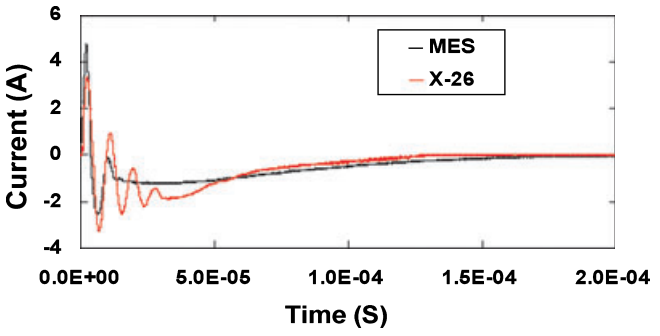

FIG. 1—*Comparison of output into identical loads of the X26 device and the MES.*

Muscle-Contraction Studies

The normalized force produced by the muscle contraction of anesthetized domestic swine was used as a measurement of effectiveness. The muscle-contraction test structure included a framework constructed of Unistrut® metal framing system (Unistrut Construction, Wayne, MI). A sling (to contain the swine), pulleys, strain gauges (Model SSM-HA-150; Interface Inc., Scottsdale, AZ), and 3/8″ by 16″ zinc eye-to-eye turnbuckles (Crown Bolts Co., Cerritos, CA) were mounted on the system. Each anaesthetized swine was placed on its dorsal surface in the sling. Twisted polypropylene truck rope (3/8-in.-diameter, Model 87054; Wellington, Madison, GA) was attached to each limb via a neoprene tennis elbow support (Wal-Mart Stores, Inc., Bentonville, AR), while the other end of the rope was attached to a turnbuckle and strain gauge. A second set of ropes was attached to each limb with neoprene-blend adjustable wrist/elbow supports (Model 483746; BD Consumer Healthcare, Franklin Lakes, NJ). Each of these latter ropes ran through a 4-in-diameter sheave block (Model SB3000FM; Tuf-Tug Products & Accessories, Moraine, OH) and were attached to a 2.27 kg (5 lbs) mass. The output of the strain gauges was quantified, displayed, and stored using equipment and software made by DATAQ Instruments, Inc. (Model DI-720-USB data acquisition system and Version 2.67 WinDaq/Pro+ software, Akron, OH). Prior to each exposure, the turnbuckles were adjusted to bring the swine's limbs to a standardized anatomical position (stretched maximally), with a baseline force of *c.* 44.5 N (10 lbs).

The measured force was normalized to the force produced by stimulations from an Advanced TASER X26 on the same pig, preceding and following the stimulation from the MES, using the same electrode positioning.

TASER device probes ("darts") were inserted subcutaneously into each animal. TASER dart placement was at a standard site (unless varied electrode spacing was studied) of: (a) one dart 5 cm to the right of mid-line, and 10 cm up from sternum; (b) second dart 5 cm off the midline to the left, at the level of the umbilicus. A distance of *c.* 30 cm between the darts was achieved. The order of the exposures in each of the experiments was varied for each animal exposed. The ordering was counterbalanced so that the average number of exposures before each of the exposure types in each sub-experiment was approximately the same.

Exposures were first performed to determine if there were any differences between muscle-contraction force due to pulses with versus without a precursor (other parameters were held constant). Next, effects of different electrode spacings were studied. Electrodes were spaced at distances of 5, 10, 15, 20, 30, and 40 cm apart.

In another series, the repetition rate of the MES was controlled by varying the firing frequency of the thyratron with a signal generator. Pulse amplitude and body current were held constant. Eight repetition rates were used (5–40 Hz, in steps of 5 Hz). Lastly, six different powers were used, corresponding to *c.* 0.5, 0.75, 1.0, 1.25, 1.5, and 1.75 times the RMS (root-mean-square) current of an X26 being discharged into the same load.

The pulse width of the X26 device was measured from when the signal first exceeded 5% of maximum until it last fell below that amount. It was noted that the pulse width varied from 1.1×10^{-4} to 1.6×10^{-4} sec. This variation was probably due to impedance variations among the different animals. To evaluate the effect of varying pulse width, the length of pulse from the MES was varied from 1.0×10^{-4} to 2.2×10^{-4} sec, by changing the storage capacitance of the MES. All other parameters were held constant.

Threshold for Ventricular Fibrillation

The total number of exposures before the start of the fibrillation experiment, in each animal, was *c.* 33. At the completion of the effectiveness experiment, the caudal TASER dart (i.e., closest to the umbilicus) was moved cranially, resulting in a separation of *c.* 15 cm between darts diagonally.

A single series of pulses from the X26 device was discharged to determine a baseline for each fibrillation experiment. The MES was then charged to a predetermined level, and fired at a rate of 20 Hz for 5 sec. The pulse shape used was similar in character to the X26 (see Fig. 1). A remote ECG (Mortara ECG Monitor) was used to monitor the function of the heart. If fibrillation did not occur, the charge voltage of the MES was increased, before repeating the discharge. If the heart was in fibrillation, the experiment was terminated and the pig was euthanized with pentobarbital sodium (Nembutal®), 100 mg-kg^{-1} intravenously, without regaining consciousness.

A calculation of the 50% probability of fibrillation threshold was performed on the basis of the data. The specific assumptions and calculation process are described in the Appendix.

Results

Muscle-Contraction Studies

Muscle-contraction force data are reported for the left hind leg in each case.

There was no significant effect of eliminating the precursor pulse on the force developed (Fig. 2). Muscle-contraction force increased as the spacing increased from 5 to 20 cm, with no further change in force above 20 cm of spacing (Fig. 3).

Muscle-contraction force increased as pulse repetition rate was increased (shown in Fig. 4). Effects of total charge on normalized force are illustrated in Fig. 5. The line represents a linear regression through the points shown (p-value = 0.0016, $R^2 = 0.16$). Increasing the pulse width and increasing the RMS body current (by changing pulse amplitude) showed similar effects on muscle-contraction force.

Threshold for Ventricular Fibrillation

Data points and the computed 50% fibrillation level are shown in Fig. 6. The UL safety margin line (10) and the IEC Publication 479 Standard line (11) are shown for comparison. The results from the stimulations in these and in the muscle-contraction studies (described above) combined are compiled in Fig. 7. Ten instances of fibrillation occurred, with none of them occurring when the X26 was operating. In calculating the level for an X26-type pulse, data from two of the animals that showed fibrillation were excluded (both were cases where the animal, at times, had great difficulty breathing without assistance between stimulations) (also, see Discussion below). At these times for other animals, the experiment was halted until the animal could both breathe on its own, and could sustain an O_2 saturation level of 90% or greater.

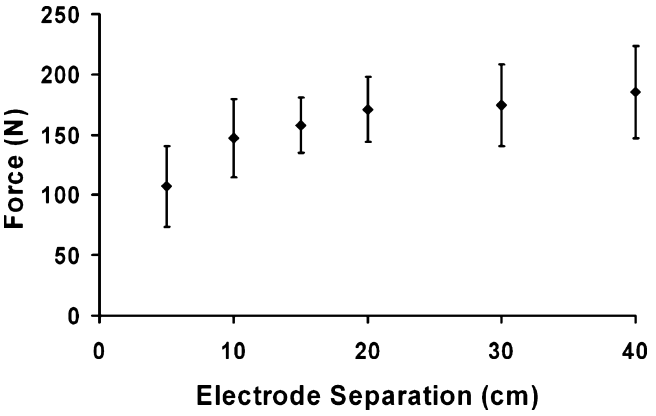

FIG. 3—*Effect of TASER device electrode spacing on leg muscle-contraction force (mean ± SD;* N = *10).*

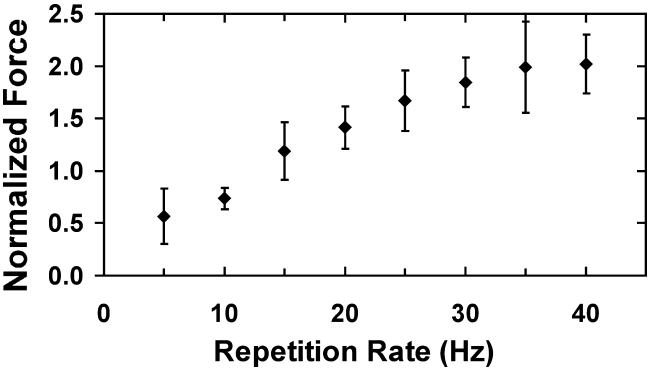

FIG. 4—*Effect of varying pulse repetition rate on normalized leg muscle-contraction force (mean ± SD;* N = *10).*

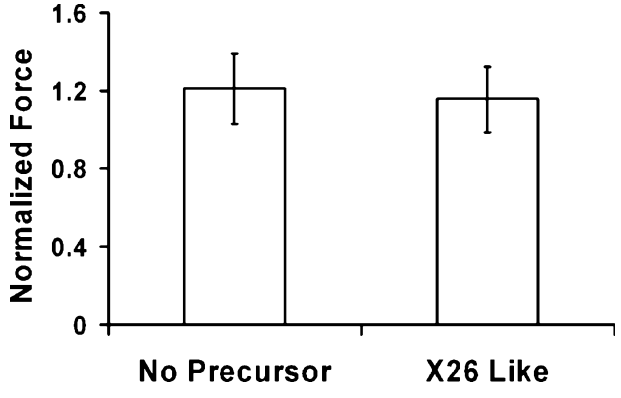

FIG. 2—*Effect of elimination of precursor pulse of X26 device on muscle-contraction normalized force (mean ± SD;* N = *10).*

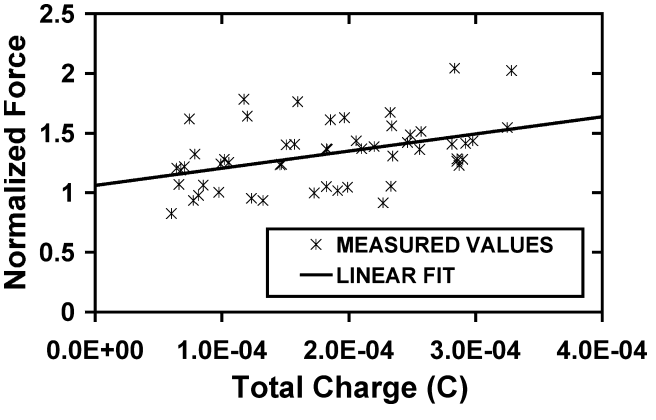

FIG. 5—*Effect of total charge on normalized leg muscle-contraction force.*

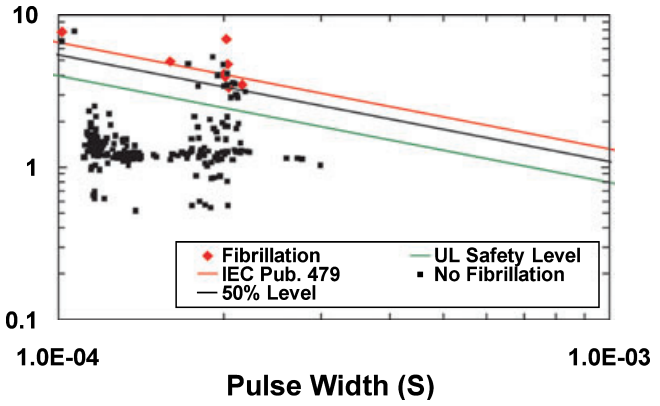

FIG. 6—*Computed 50% fibrillation level and summary of data used in comparison with accepted electric safety standards.*

Discussion

The pre-pulse of the X26 waveform produces a very high voltage. The intention of the very high voltage is to create a small plasma channel (i.e., a spark) between the end of a TASER device dart and a target's skin, if the dart has not penetrated the skin. The plasma channel acts as a conduction path for the main lower voltage pulse into the target.

Elimination of the pre-pulse from the X26-like pulses did not have a statistically measurable effect on the normalized force measured. This implies that future studies could be conducted using pulse shapes that do not have the pre-pulse and still be valid in terms of overall effectiveness. Despite this lack of effect of the precursor on muscle-contraction force, as measured in our experiments, however, the presence of an air gap is a common situation during use of a TASER device in law-enforcement situations. Therefore, if one or both probes are in contact with clothing rather than skin, the precursor pulse may be very important.

On the basis of anecdotal reports, it was expected that the magnitude of force would depend fairly strongly on electrode spacing. After a minimum spacing of 20 cm had been achieved, maximum force was obtained. Therefore, it is suggested that any future developments of new conducted energy weapons should include placement of electrodes a minimum of 20 cm apart so that efficiency of the system is not degraded.

It is possible that a greater variation in pulse width could have had a greater effect on muscle-contraction force. The animals in the current experiments may have been stimulated to such an extent that increases in the MES input could have only a limited effect.

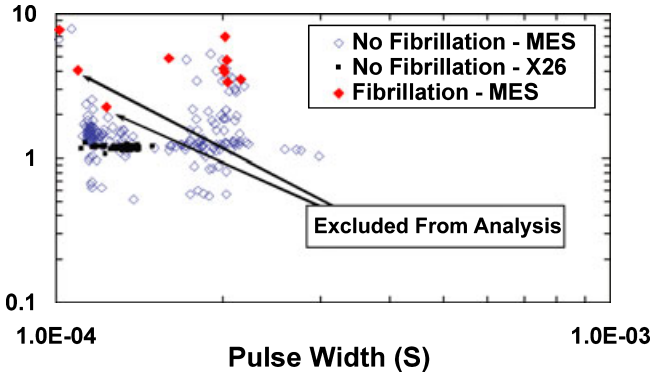

FIG. 7—*Summary of data from all electronic control device exposures. There were 91 exposures from the X26, none of which caused fibrillation, and 208 exposures from the MES, 10 of which caused fibrillation.*

As mentioned in the Results section above, data from two animals that showed fibrillation were excluded from analysis of ventricular fibrillation (both were cases where these animals exhibited difficulty in breathing without assistance between stimulations). One may question whether the animals were (a) oversedated and therefore apneic, or (b) in too low of an anesthetic plane and therefore struggling with subsequent difficulty in breathing. Absence of both reflexes and lack of jaw tone were indicative of a suitable anesthesia plane. Although the incidence of apnea has been reported to be lower in animals receiving propofol than in those given other agents such as ketamine (12), the two animals mentioned in our study exhibited difficulty in breathing and lowered O_2 saturation levels. Since hypoxia may result in a greater susceptibility to ventricular fibrillation (13,14), we believed valid analysis could only be accomplished by omitting data from the two animals mentioned.

In one of the earliest studies relating to conducted energy weapons, investigators failed to induce cardiac arrhythmias in dog hearts with direct application of "stun guns" (15). More recently, Stratbucker et al. (16) and McDaniel et al. (17) found a lack of change in heart rate and blood pressure, and no ventricular fibrillation, in anesthetized swine exposed to 5-sec discharges of the TASER X26 device waveform. Stratbucker et al. (18) also performed theoretical calculations relating to fibrillation threshold values. Both the experimental results of that research group (16,17) and our current results are consistent with a low likelihood of fibrillation, as predicted by the calculations.

In studies of conscious human volunteers (19,20), although heart rate increased, there were no significant cardiac dysrhythmias immediately after exposure to the X26 device. On the basis of experiments with anesthetized swine, Nanthakumar et al. (21) suggested that discharges from the TASER X26 device were more likely to stimulate the myocardium than from TASER International's M26 device. Interestingly, Lakkireddy et al. (22) found that cocaine actually reduced vulnerability of the swine heart to ventricular fibrillation.

In another study (23), although repeated periods of X26-device exposure (with only short recovery periods of a few seconds) resulted in death in 60% of animals, there were no episodes of ventricular fibrillation. Instead, nonsurvivors initially exhibited apnea, rather than immediate cardiac effects. The animals in that series were extremely hyperkalemic and acidemic.

In another study of swine by Dennis et al. (24), two out of eight animals died due to ventricular fibrillation following two 40-sec applications of a TASER X26 device. The animals in that study, however, were anesthetized with ketamine/xylazine. Effects of ketamine/xylazine in relation to hypoxia ventricular fibrillation have been discussed previously (25). Whether these effects of ketamine or xylazine explain, in part, death in the series of Dennis et al. is unknown.

Differences between the MES used in the present experiments and similar devices used by other investigators (also designed to study effects of increasing parameters on ventricular fibrillation) would not appear to be operationally significant. The device used by McDaniel et al. (17) delivered discharges at a fixed voltage of 6000 V. Both that device and the MES could be varied, in terms of output capacitance, as a multiple of the nominal capacitance of the X26.

In our current study, the 50% probability of fibrillation level of X26-like pulses ranged from 4 to 5 times higher than the X26.

Relatively large variations about the X26 operating level were found not to result in fibrillation or asystole. Therefore, it should be possible to design and build an X26-type device that operates efficiently at levels higher than the X26. Ideker and Dosdall (26) and Holden et al. (27) also concluded that ventricular fibrillation was highly unlikely to occur as a result of any direct effect of X26 pulses on the heart.

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Appendix

We assumed a Gaussian distribution of probability of responses to electric shock. Regions of constant probability of response were assumed to be straight lines (isoclines) on a log-log plot of RMS body current versus duration of pulse. The basis of this assumption was the observation that the UL safety margin line and the IEC Publication 479 Standard line are parallel in the region of interest (duration of pulse from 10^{-4} to 10^{-3} sec). Thus, even though the two standards had different criteria for determining biological effects, the probability to cause that effect could be plotted as a straight line on a log-log plot.

The slopes of the IEC 479 line and the UL safety line are identical, so we used the same slope, −0.7, as the slope of the isoclines (Fig. 6). This assumption implies that only the intercept is the important parameter in determining the result of an electric shock. It is also assumed that the sensitivity of the fibrillation response is a Gaussian shaped distribution function of a single parameter, which we will refer to as b.

To treat the unique trials statistically, a definition for the probability of fibrillation based upon groups of tests at a particular isocline is needed. To do that, all the isoclines within a specified region, b, are assumed to have the same probability of effect. By counting the number of tests and animals that exhibited fibrillation within each line, a probability of response is calculated for each isocline. The data can then be fitted to determine the 50% mean

threshold for effect and the standard deviation in the distribution. This is accomplished by calculating an argument to the error function, equivalent to each of the probabilities found for each isocline b,

$$p_i = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y_i} e^{-\xi^2/2} d\xi$$

then finding the best linear fit of the data Y_i vs. b_i.

$$Y = \alpha b + \beta$$

The slope of the fit α corresponds to $1/\sigma$ where σ is the standard deviation or width of the Gaussian distribution. The x-intercept of the fit $-\beta/\alpha$ corresponds to the 50% mean threshold value. For the data in Fig. 3, choosing $\Delta b/b = 1/100$ yields $\sigma = 1.2137$ and $\beta = 2.1603$. Isocline values representing other threshold probability values can be determined by

$$b_{p\%} = \sigma(\mathrm{erf}^{-1}(p\%/100) - \beta)$$

where $b_{p\%}$ = y-intercept of the isocline related to the probability $p\%$ of causing fibrillation and $\mathrm{erf}^{-1}(x)$ is the inverse Error Function. This intercept would then be plotted with slope = −0.7 on the log-log plot in Fig. 6 to indicate the combination of RMS current and pulse widths that would induce fibrillation in $p\%$ of the exposures.

Of note, variations in the choice of Δb affect the values of the 50% threshold and the standard deviation. However, the variation causes only a 1% change in b as Δb was varied by factor of 10. Also, due to the binary nature of the data (no fibrillation vs. fibrillation), there must exist a minimal number of trials per isocline to generate useful probability data. Therefore, there exists a lower constraint upon the size of Δb before the linear fit of the data breaks down. For this data, $\Delta b/b = 1/100$ was chosen as an optimal value based upon the R-square values from the linear regression of the data.