

## ELECTROMUSCULAR INCAPACITATING DEVICE SAFETY

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**Abstract:** Electromuscular incapacitating devices (EMD) are known as stun guns, or Tasers®. This paper will present methods and preliminary results to determine if Tasers can directly electrocute the heart. Our goal is to develop safety standards that can be used in a bench test for EMDs without animal experiments. By combining our results from finite element modelling and existing studies done at 60 Hz, we develop methods of determining the dart-to-heart distance causing ventricular fibrillation (VF) and a bench test standard based on waveform charge density.

### Introduction

Electromuscular incapacitating devices (EMDs), such as Tasers, provide less lethal options designed to temporarily incapacitate, confuse, delay, or restrain an adversary in a variety of situations. EMDs generate short duration electrical pulses [1]. The effective charge delivered to the subject may excite the heart and cause VF. Amesty International states that 70 people have died after being Tasered [2]. The implication is that Tasers are killing these people. Thus some jurisdictions have banned Tasers and police then use bullets to incapacitate. There is also a recent case [3] of VF after a Taser discharge. Alternative hypotheses for death following EMD shock include positional asphyxia, skeletal muscle damage causing hyperkalemia and acidosis, heat and drugs [4]. Tests on swine show a cardiac safety factor of 15 to 42 [5], and recent report findings also indicate that stun guns are relatively safe [6]. This paper proposes a FEM model to estimate the minimum dart-to-heart distance where EMD can not directly cause VF.

### Methods

*Membrane Excitation Model:* A membrane under subthreshold conditions can be described by a uniformly distributed leakage resistance and parallel capacitance [7]. When a stimulus current depolarizes the resting membrane beyond the threshold voltage, an action potential is generated and the cell is excited. The minimum required stimulus constant current  $I$  of duration  $d$  can be expressed as,

$$I = \frac{V_{th}}{R_m(1 - e^{-\frac{d}{\tau}})} = \frac{b}{1 - e^{-\frac{d}{\tau}}} \quad (1)$$

where  $V_{th}$  is the threshold voltage (about 20 mV for excitation);  $d$  is the stimulus duration;  $\tau$  is the membrane time constant, which is equal to the lumped membrane resistance  $R_m$  times the lumped membrane capacitance  $C_m$ ;  $b$ , the rheobasic current, is the minimum stimulating current needed for long durations and is equal to

$$b = \frac{V_{th}}{R_m} \quad (2)$$

$\tau$  is the membrane time constant, which is equal to the lumped membrane resistance  $R_m$  times the lumped membrane capacitance  $C_m$ . That is,

$$\tau = R_m C_m \quad (3)$$

*Strength–Duration Curve:* The strength–duration curve shown in Figure 1 was described by Geddes and Baker [7] for the relation between the minimum required stimulus current to excite cells and the pulse duration. The analytical strength–duration curve can be directly derived from the membrane excitation model in equation (1).

It is easy to show charge  $Q = Id$  remains approximately constant for short duration pulses.

$$Q = Id = \frac{bd}{1 - e^{-\frac{d}{\tau}}} \quad (4)$$

For short duration pulses where  $d/\tau$  is small, the threshold charge  $Q$  is approximately constant since for small  $d/\tau$ ,

$$e^{-\frac{d}{\tau}} \approx 1 - \frac{d}{\tau} \quad (5)$$

Thus equation (4) reduces to

$$Q = b\tau \quad (6)$$

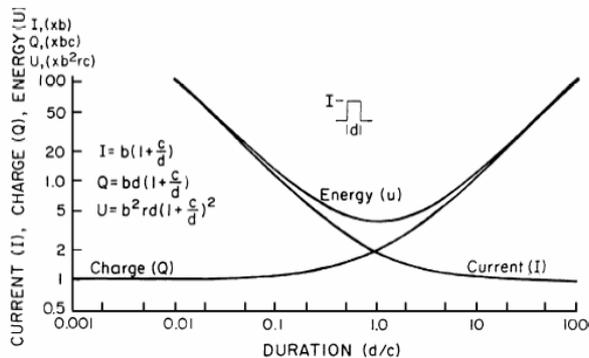


Figure 1: Normalized Current, Charge and Energy with Respect to Normalized Stimulus Duration  $c$  is the Chronaxie and is Equal to  $0.693 \tau$  [7]

**Current Density:** When we discuss membrane excitation, it is more useful to use current density  $J$  rather than current  $I$ , because it constrains our discussion to a constant number of cells within a unit area. The current density is defined as current per area ( $J = I/A$ ). For long duration excitations ( $d$  10 times longer than  $\tau$ ), the required current density for excitation approaches a constant value. However, for short duration excitations ( $d$  10 times shorter than  $\tau$ ), the required current density increases exponentially, as shown in Figure 1.

**Charge Density:** Equation (6) shows that for a short duration excitation, the required charge for excitation approaches a constant value. To discuss the amount of charge acting on a constant number of cells, we also use charge density  $D$  rather than charge for the following discussion. The charge density is defined as charge per unit area ( $D = Q/A$ ). It reaches a minimum value for short duration currents as shown in Figure 1. We define the required charge density for short duration excitation to cause VF as  $D_{VF}$ .

**Excitation and Ventricular Fibrillation:** To generate an extrasystole a small number of cardiac cells need to be depolarized. However, to cause VF a critical mass of cardiac cells needs to be excited during the early phase of recovery where higher currents are required [8, page 189]. VF thresholds similar to excitation thresholds follow a strength–duration curve but it is shifted up by a factor that varies depending on the type and position of the electrodes used. For a bipolar electrode consisting of two wires wrapped around an insulating tube and sutured to the myocardium of dogs, Jones and Geddes [9] found that excitation thresholds have a strength–duration curve with time constant equal to 0.25 ms whereas VF thresholds curves have a time constant equal to 1.7 ms. Thus the ratio of VF to excitation threshold varies between 150 and 50 as the duration of the stimulus is increased from 1 ms to 10 ms.

**60 Hz VF Thresholds:** VF thresholds at 60 Hz are extensively studied and standards are widely developed. A review paper [10] of these studies shows that despite the different conditions under which each experiment is performed, the fibrillating current density for 60 Hz decreases with increased area and approaches a minimum RMS value of  $5 \mu\text{A}/\text{mm}^2$ , i.e. a single peak value of  $7.1 \mu\text{A}/\text{mm}^2$ , as shown in Figure 2.

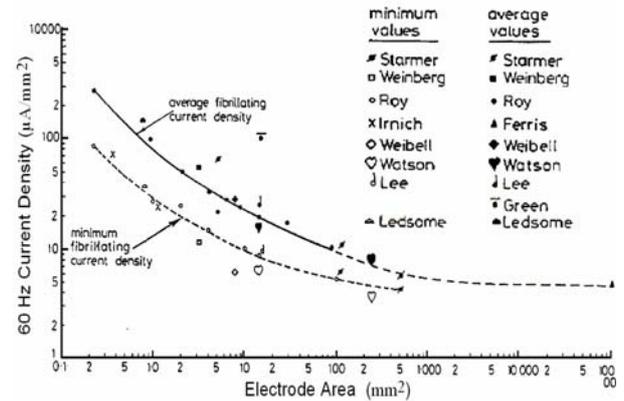


Figure 2: Fibrillating Current Density Decreases with Increased Electrode Area [10]

This threshold is obtained for duration of exposure to the 60 Hz stimulus exceeding 1 s. Reilly [8, page 212] shows that there is at least a 10 times increase in VF thresholds for duration of exposure shorter than 20 ms where we can view the 60 Hz current as a single stimulus. At durations less than 1 cycle (16 ms), we can consider the 60 Hz current as a single stimulus of duration equal to half the period (8 ms). Therefore, the single peak minimum fibrillating current density for an 8 ms single stimulus is at least  $71 \mu\text{A}/\text{mm}^2$ . Including the factor of area in equation (1) with time constant for VF equal to 1.7 ms as mentioned above, we can use the current density found at 8 ms to approximate the rheobasic fibrillating single peak current density (denoted as  $J_b$ ) as

$$J_b = \frac{b}{A} \quad (7)$$

In this study,  $J_b = 70 \mu\text{A}/\text{mm}^2$  is chosen.

Figure 3 summarizes the previous discussion: Point A represents the single peak fibrillating current density for 60 Hz with exposure time longer than 1 s [10]. Then, we can move to point B which shows the VF threshold for single stimulus of duration 8 ms [8, page 212]. For short duration pulses at C, such as Tasers, we can move along the upper strength–duration curve whose time constant is 1.7 ms to predict the VF threshold. The lowest strength–duration curve has a time constant of 0.25 ms and it shows that at 8 ms (point D) the excitation threshold is 60 times less than that at point B [9].

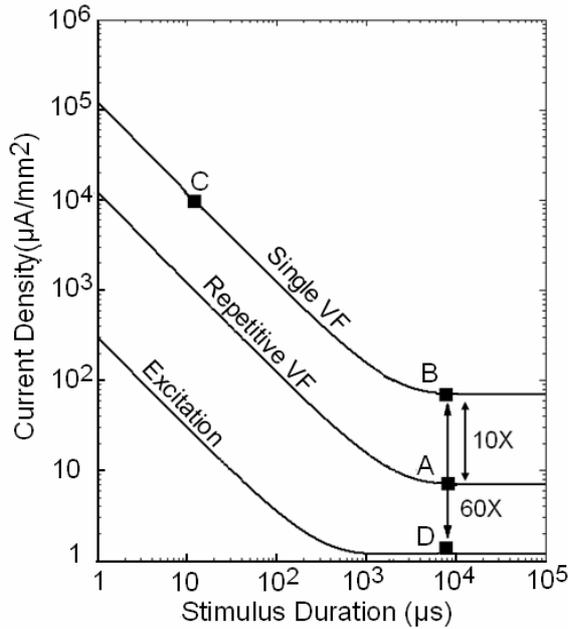


Figure 3: Ventricular and Excitation Thresholds for Different Stimulus Duration

*Taser waveforms:* EMDs generate voltages of about 50 kV, currents of about 2 to 15 A, pulse durations of about 10 to 80 µs, repetition rates of about 20 pulses/s, for about 5 s [1]. Figure 4 shows measured waveforms for one pulse of the X26 and M26 Taser. At these short duration pulses, the maximum depolarization voltage depends only on the amount of charge delivered across the capacitor. As an example, for the M26, it is the charge delivered during the first half period (7.8 µs) that determines the fibrillating threshold and for the X26 it is the charge delivered during the first 164 µs. Figure 4 shows the M26 and the X26 waveforms for a typical load of 300 Ω. By integrating the current waveforms, we can obtain the maximum charge delivered by the X26 which is 130 µC at 164 µs and by the M26 which is 103 µC at 7.8 µs.

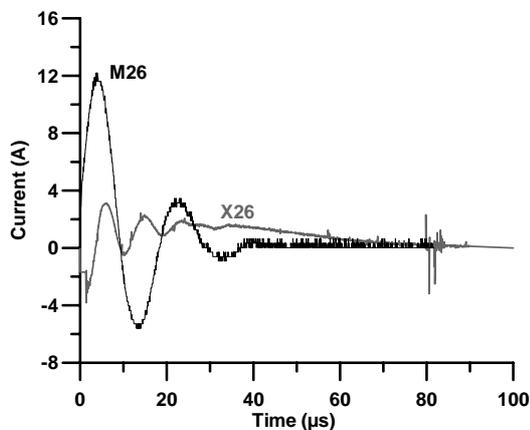


Figure 4: Taser Waveforms Measured at a 300 Ω Load Typical of the Body

These observations can be further verified by applying the Taser waveforms to a parallel RC model. Assuming that 20 mV can excite the cell [7], we can use equation (2) with the previously found rheobasic current density of 70 µA/mm<sup>2</sup> to yield  $R = 286 \Omega$ . Knowing that the time constant for fibrillation is 1.7 ms yields  $C = 5.9 \mu\text{F}$ . Figure 5 shows that the maximum voltage is attained at 7.5 µs for the M26 and at 127 µs for the X26.

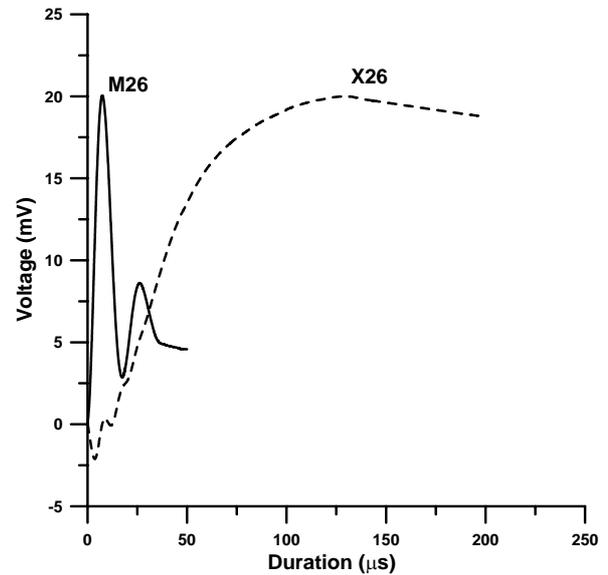


Figure 5: Simulated Membrane Depolarization Behavior for the X26 and M26 Tasers

*Predicting the VF Threshold for EMD:* To find the VF threshold for EMDs we need to approximate the minimum fibrillating charge density denoted as  $D_{VF}$ , which approaches a constant value for typical EMD durations. Including the area factor, we can use equation (6) to relate the charge density to the rheobasic current density which we found earlier to yield

$$D_{VF} = J_b \tau \quad (8)$$

Although EMD stimuli are applied for 2 to 5 s, they cannot be considered as repetitive stimuli since the current impulses are delivered at very low duty cycle (less than 0.003 [11]) so that effect of each pulse is isolated from the others. Studies have shown that for duty cycle less than 0.1, the effect of prolonged stimulation no longer decreases VF threshold [12]. Therefore, for EMD thresholds we can use the rheobasic current density found above for a single stimulus which is 70 µA/mm<sup>2</sup>. Substituting into equation (8) with  $\tau$  equals 1.7 ms yields a minimum fibrillating charge density for EMD of 119 nC/mm<sup>2</sup>. Figure 6 shows the variation of charge and current density with respect to stimulus duration for VF thresholds. It shows that charge density, unlike current

density, decreases for a short duration stimulus and reaches a minimum for durations shorter than 200  $\mu\text{s}$ .

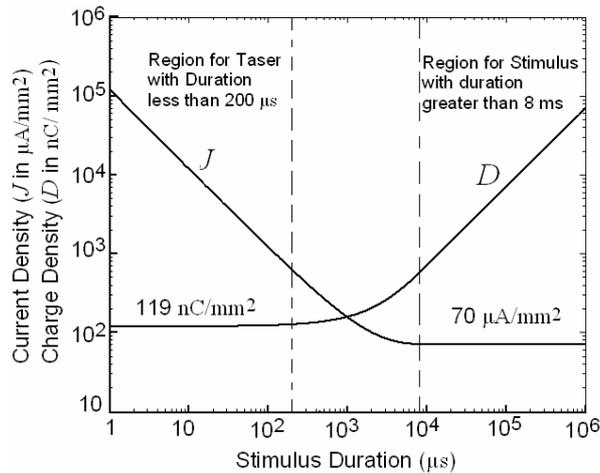


Figure 6: The Variation of Charge and Current Density with Respect to Stimulus Duration for VF Thresholds

*Finite Element Modelling of Current Density Inside Heart:* The effect of the electrode geometry and tissue properties on the current density can be determined by finite element method (FEM) modelling. A simple axisymmetric FEM [13] model can calculate and estimate current density around the Taser dart.

*Bench Test Standard for EMD:* The idea of the bench test standard without experiments on live animals follows: We have the rheobasic current density  $J_b$  causing VF ( $70 \mu\text{A}/\text{mm}^2$  is chosen in this study) and the time constant  $\tau$  (1.7 ms) that causes VF, we can obtain the charge density  $D_{VF}$  for the Taser causing VF according to equation (8) as stated above. Thus for any EMD, we can measure its current waveform at a typical load ( $300 \Omega$  in this study), we can compute the maximum charge  $Q_x$  delivered by integration. Then based on the FEM modelling results, we can obtain the current density  $J$  at any location of the body for any current value  $I$  inserted into the dart (here 1 A is chosen for convenience). For the measured current the charge density  $D_x$  is

$$D_x = \frac{J}{I} \times Q_x \quad (9)$$

where  $J$  is the current density determined by the FEM model for inserted current  $I$ .

Then if the resulting charge density  $D_x$  at a distance from the heart is less than the fibrillating charge density  $D_{VF}$  ( $D_{VF} = 119 \text{ nC}/\text{mm}^2$ ) then the EMD is safe at the given distance from the heart. In sum, this criteria is

$$J < I \times \frac{D_{VF}}{Q_x} = I \times \frac{J_b \tau}{Q_x} \quad (10)$$

where  $Q_x$  is the charge of the given current waveform;  $D_{VF}$  is charge density VF threshold;  $J_b$  is the rheobasic current density VF threshold and  $\tau_b$  is the VF time constant.

Hence, for a location inside the tissue (such as the heart location nearest the dart), if equation (10) is satisfied, that location is safe from VF. The minimum dart-to-heart distance at which the given EMD can not directly cause VF is estimated by the minimum dart-to-heart distance at which the current density satisfies equation (10).

## Results

We created our initial computer model of Taser current density using MSC Patran 2001 r2a and Abaqus 6.3.1 on a Sun Blade 1000 workstation with 2.5 GB memory, and Matlab 7.0.4 on Windows XP 5.1 with 1 GB memory. The model is a 2-D axisymmetric model with cross section of size  $150 \text{ mm} \times 250 \text{ mm}$  and uniform conductivities. The Taser dart has a length of 9 mm and diameter of 1 mm. 1 A current is applied to the dart at the center of the top surface and flows to the ground on both sides and the bottom surface. The mesh size around the dart (the  $40 \text{ mm} \times 20 \text{ mm}$  area) is 0.5 mm. The outside mesh size is 2 mm.

Figure 7 shows a zoom-in view ( $20 \text{ mm} \times 20 \text{ mm}$ ) of the current density contour around the dart for 1 A inserted current. The dart geometry is marked using dotted lines. Note that the maximum current density is at the tip of the dart and the current density decreases rapidly away from the dart tip. Linear interpolation and average current density for each element are used in Figure 7.

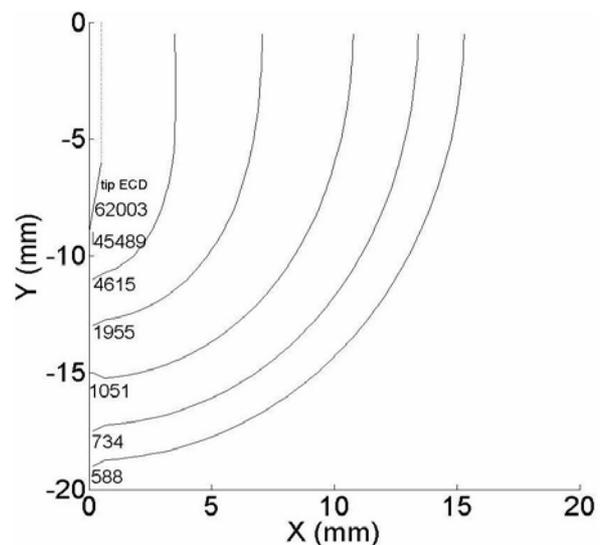


Figure 7: Zoom-in View of Current Density  $J(\mu\text{A}/\text{mm}^2)$  Contour Around the Taser Dart Electrode for 1 A Inserted Current

Figure 8 shows the log scale current density  $J$  ( $\mu\text{A}/\text{mm}^2$ ) for 1 A inserted current on the  $y$ -axis (actually drawn using data in the range of  $x < 0.5 \text{ mm}$ )

versus the distance to the dart tip. Nearest neighbor interpolation and current density at nodes are used in Figure 8.

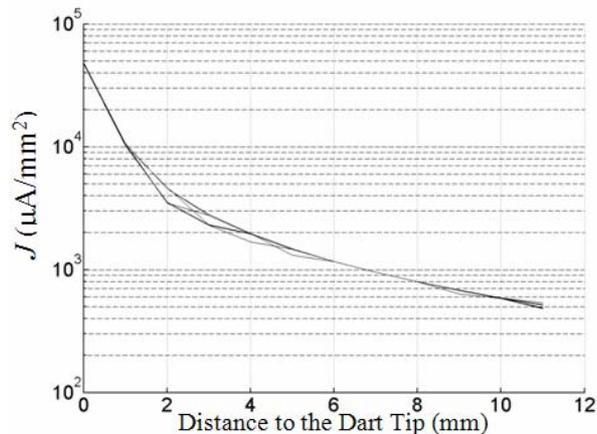


Figure 8: Current Density  $J$  ( $\mu\text{A}/\text{mm}^2$ ) Along the Axis ( $x < 0.5$  mm) for 1 A Inserted Current in the Axisymmetric Model Versus the Distance to Dart Tip ( $= 9 - y$ )

As an example we use the X26 and M26 waveforms shown in Figure 4 to find the dart-to-heart distance at which no VF occurs. In our FEM model, we use 1 A current ( $I = 1$  A) through the dart for convenience. We use the  $119 \text{ nC}/\text{mm}^2$  charge density fibrillating threshold ( $D_{VF} = 119 \text{ nC}/\text{mm}^2$ ) predicted above. For the X26,  $Q_x = 130 \mu\text{C}$ . Substituting into equation (10), the fibrillating current density is  $915 \mu\text{A}/\text{mm}^2$ . Using Figure 8, the minimum dart-to-heart distance where VF does not occur for the X26 would be about 7 mm. Similarly for the M26,  $Q_x = 103 \mu\text{C}$ ; the fibrillating current density is  $1155 \mu\text{A}/\text{mm}^2$  and the minimum dart-to-heart distance is about 6 mm.

## Discussion

The assumptions we made for the FEM model include: the tissue has uniform conductivity and is axisymmetric; the contour map interpolation does not change the values to the extent sensitive to our conclusion; and the  $150 \text{ mm} \times 250 \text{ mm}$  model results are similar to those that would be obtained from a full torso model. One current limitation of the FEM model is a lack of data on tissue properties. Electrical tissue properties vary with locations in the body. The Taser waveforms could vary with different Tasers, and different individual Taser impulses. We just used one waveform as an example. These limitations may lead to misleading model results, which have to be considered if models are to be used to predict the safe dart-to-heart distance.

We attempted to use the human anatomy data from Yale [14] which are already segmented, however, we found skin tissues inside the body. Currently we are attempting to use the Utah torso data [15], which are

meshed and conductivities are assigned for each mesh. However, we need finer mesh size around the dart electrode, while the Utah torso mesh size may not be small enough. Finally, we may start from the Visible Human raw data [16], do segmentation and assign the conductivities.

No model should be used without verification. No institutional review board would permit tests to measure VF on humans. Therefore we will determine the VF current density and dart-to-heart distance during tests on anesthetized swine, which will feel no pain. Results of these tests will likely change our initial estimates above. To compare with the results on swine, we plan to build a FEM model for swine.

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