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Medical safety of TASER conducted energy weapon in a hybrid 3-point deployment mode

Dorin Panescu, Ph.D.*, Mark W. Kroll, Ph.D.** and Robert A. Stratbucker, M.D., Ph.D.***

* - NewCardio, Inc., Santa Clara, CA, ** - Cal Poly University, San Luis Obispo, CA, *** - Stratbucker & Assoc

Introduction: **TASER conducted energy weapons (CEW) deliver electrical pulses that can temporarily incapacitate subjects. The goal of this paper is to analyze the distribution of TASER CEW currents in the heart and surrounding organs and to understand theoretical chances of triggering cardiac arrhythmias, of capturing the vagus and phrenic nerves and producing electroporation of skeletal muscle structures. The CEW operates in either probe mode or drive-stun (direct contact) mode. There is also a hybrid mode in which current is passed from a single probe to either or both of 2 drive-stun electrodes on the weapon, presumed to be in direct contact with the skin.**

Methods and Results: **The models analyzed herein describe strength-duration thresholds for myocyte excitation and ventricular fibrillation (VF) induction. Finite element modeling (FEM) was used to approximate current density in the heart for worst-case TASER electrode placement. The FEMs theoretically estimated that maximum TASER CEW current densities in the heart and in neighboring organs are at safe levels. A 3-point deployment mode was compared to probe-mode deployment. The margins of safety for the 3-point deployment were estimated to be as high as or higher than for the probe-mode deployment.**

Conclusion: **Numerical modeling estimated that TASER CEWs were expected to be safe when deployed in 3-point mode. In drive-stun, probe-mode or 3-point deployments, the CEWs had high theoretically approximated safety margins for cardiac capture, VF, phrenic or vagus nerve capture and skeletal muscle damage by electroporation.**

Keywords — **Arrhythmia, Modeling, Cardiac, Fibrillation, TASER.**

I. INTRODUCTION

Less-lethal weapons (LLW) provide military and law enforcement personnel with a tool to resolve conflict with a proportionate, lawful, appropriate and necessary use of force. An increasingly popular LLW is the conducted energy weapon (CEW). These weapons, such as TASER devices, deliver trains of brief, high-voltage but low-charge electrical pulses designed to temporarily incapacitate subjects through strong neuromuscular activation. TASERs utilize compressed nitrogen to project two small probes to distances of 4.5, 6.5, 7.5 or 10.5 m at a speed of over 48 m/s [1]. Paintball guns used for recreational play are metered at around 60 m/s. An electrical signal is transmitted through trailing wires to where the probes make contact with the body, or clothing, resulting in an immediate loss of the person's neuromuscular control, with the initial reaction being a gravitational dysreflexia (i.e. fall to the ground), and loss of ability to perform coordinated action for the duration of the impulse. The method of incapacitation is through electrical activation of skeletal muscle tissue innervated by peripheral nerves within the electric field created by the TASER device [1]. The stimuli from a TASER will override the motor nervous system and block the command and control of the human body. Conventional stun devices stimulate sensory neurons for pain compliance and can be over-ridden by a focused individual. The TASER devices directly stimulate pre-endplate motor nerve tissue, causing incapacitation regardless of subject's mental focus, training, size, or drug-induced dementia [2]. The most popular TASER CEW models supplied to law enforcement agencies are the M26 and X26. Their typical output waveforms are shown in Figs. 1 and 2, respectively. Table I provides a specification summary for these two devices [3].

Table I. Specifications of TASER M26 and X26 CEWs.

Specification	M26	X26
Open-circuit peak voltage [kV]	50	50
Peak voltage in typical load [kV]	5	1.2
Average output voltage over pulse duration [V]	3800	600
Energy delivered in typical load [J/pulse]	0.5	0.1
Power into typical load [W]	10	1.9
Charge in the main phase [μC]	85	100
Net charge [μC]	32	100
Overall pulse duration [μs]	40	100
Pulse rate [pulse/s]	20 ± 25%	19
Total delivery duration [s]	5	5
On-demand delivery termination	Yes	Yes
Power source	8 NiMH rechargeable or Alkaline AA cells	Two 3 V Li CR123 cells

This study analyzes the theoretical distributions of TASER currents through various tissues and estimates the VF risk.

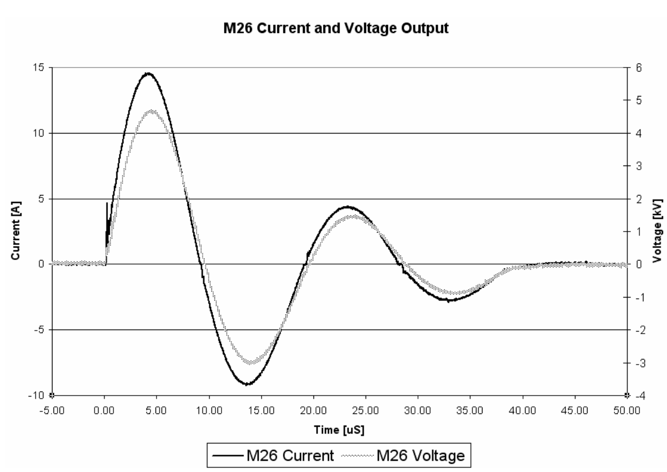

Fig. 1. TASER M26 output for a 400 Ω load.

II. METHODS

We used the strength-duration curve in Fig. 3 to estimate the risk of electrically-induced VF events [4]. Parameter *c* represents the chronaxie of the cardiac myocyte. Based on a literature survey, Sun *et al.* found that the rheobasic current density (i.e. for very long durations – or $d/c > 10$) required to induce VF equals 7 mA/cm^2 [5, 6].

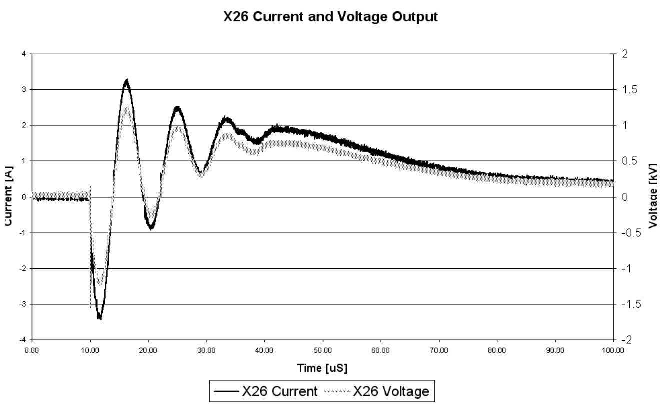

Fig. 2. TASER X26 output for a 400 Ω load.

The longest duration of the main phase TASER current is about 100 μs, for the X26 model. The myocyte chronaxie is 1.2 ms, for a VF induction model [4, 6]. Thus, the corresponding *d/c* value is 0.08 (for a *c/d* value of 12).

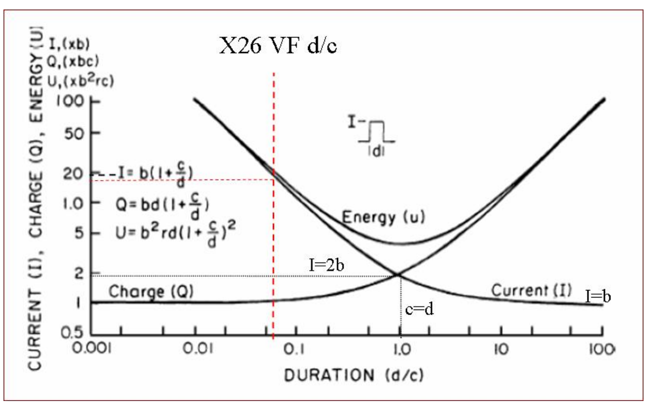

Fig. 3. Strength-duration curves for *I*, *Q* and *U* and the *d/c* ratio and rheobase multiple for X26 waveform parameters.

Therefore, using Fig. 3, the corresponding current density thresholds required to induce VF is 91 mA/cm^2 (i.e. $91 = 7*(1+12)$). For increased cardiac safety, the CEW current density in the heart volume should be less than 91 mA/cm^2. Ideker *et al.* indicated even greater chronaxies of 2.5 – 3.5 ms [7]. Use of a greater chronaxie level would result in increased VF induction current density (*J*) threshold and, thereby, an increased margin of safety. We use a VF *J* threshold of 91 mA/cm^2 that covered worst-case scenario situations. Employing same formulas as above, the resulting theoretical VF induction threshold for a TASER M26 CEW is estimated to be 847 mA/cm^2. A finite element model (FEM) was used to numerically approximate currents delivered during TASER M26 discharges and then to compare them to this VF current density threshold. The FEM had the following characteristics (Fig. 4):

- Muscle (neck, shoulder, limbs)
- Bone (spine, ribcage)
- Heart
- Lungs
- Skin/Fat
- Abdomen
- TASER electrodes were located such that to simulate real-life deployment conditions
- Model was 176 cm long and 44 cm wide at shoulder level
- Voltage boundary conditions: 5000 V (TASER M26 peak voltage)
- Models computed steady-state solution

The model consisted of 8460 hexahedral elements. The FE region resistivities were based on previous published reports (Table II) [8].

Table II. Finite element model material properties.

Region	Resistivity [Ω·cm]
Skin/Fat	2200
Lungs	1100
Bone	5000
Heart	450
Abdomen	200
Muscle	300
Electrodes	0.001

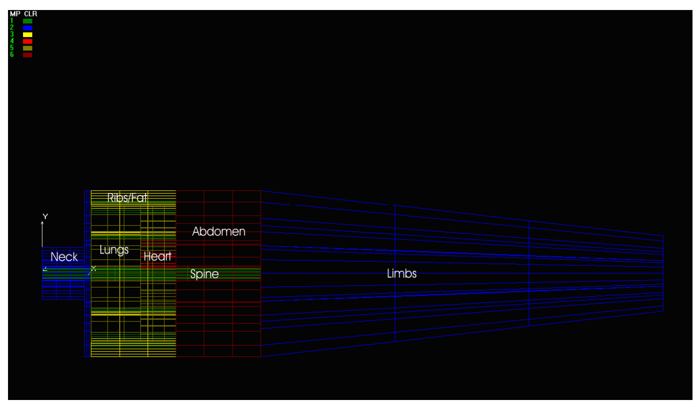

Fig. 4. The FE mesh includes 7 regions.

Since Cosmos, the FE software used in this study [9], solved for steady state, rather than transient solutions, the applied voltage was set at 5000 V, in the range of loaded output peak voltages for TASER M26 devices.

III. RESULTS

Concerns have been particularly raised about use of TASER CEWs in 3-point deployment mode, with two drive-stun electrodes on a suspect's back and a probe electrode lodged into the suspect's chest. Figure 5 shows the voltage distribution on the surface of such model. As seen, the voltage decreases rapidly with distance away from electrodes. Figure 6 shows a comparison of theoretically estimated current densities delivered by a TASER M26

CEW in 3-point vs. probe-mode deployments. In both modes, the current density was significantly attenuated by the time it reached into deep body tissue layers. Current density color maps are plotted through cross sections taken at the heart level. The right chest, back and heart volumes are labeled to help with orientation. The upper parts of the two current-density color maps clearly show that the theoretically estimated current density under the probe-mode electrode (right map) is expected to decrease significantly when the drive-stun electrodes are fully applied to the back of the suspect, as in the case of a 3-point deployment (left map). Similarly, the bottom sections of these maps also show that, for a 3-point deployment, the TASER CEW current is theoretically expected to be shunted between the two drive-stun electrodes and not penetrate deep into tissues. Table III compares the computed current density, electric field and safety margins for these two placements. The electric field and current density values are the maximum values read in and around the volume that modeled the heart. As known from literature, the phrenic and vagus nerves and the diaphragm all reside in very close proximity to the heart volume. Consequently, the numbers in Table III cover maximum theoretical values for the heart, phrenic/vagus nerve and diaphragm. The data theoretically predict that the TASER M26 CEW deployed in probe-mode produces about 50 % higher electric field strength and current densities in the volumes described. Considering the safety thresholds (i.e. for cardiac capture, VF, nerve capture and skeletal muscle damage by electroporation) presented above and in the literature [4-7, 10-12], the FEM analyses above underline the scientific expectation that the TASER M26 CEW electrodes applied in 3-point mode yield much higher safety margins.

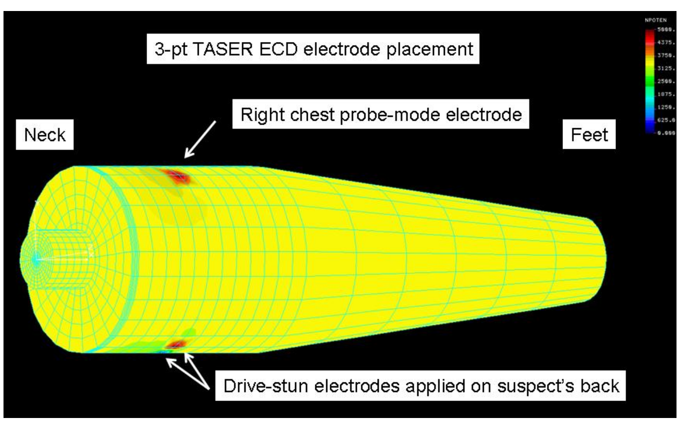

Fig. 5. Theoretical voltage distribution by a TASER M26 deployed in a 3-pt mode.

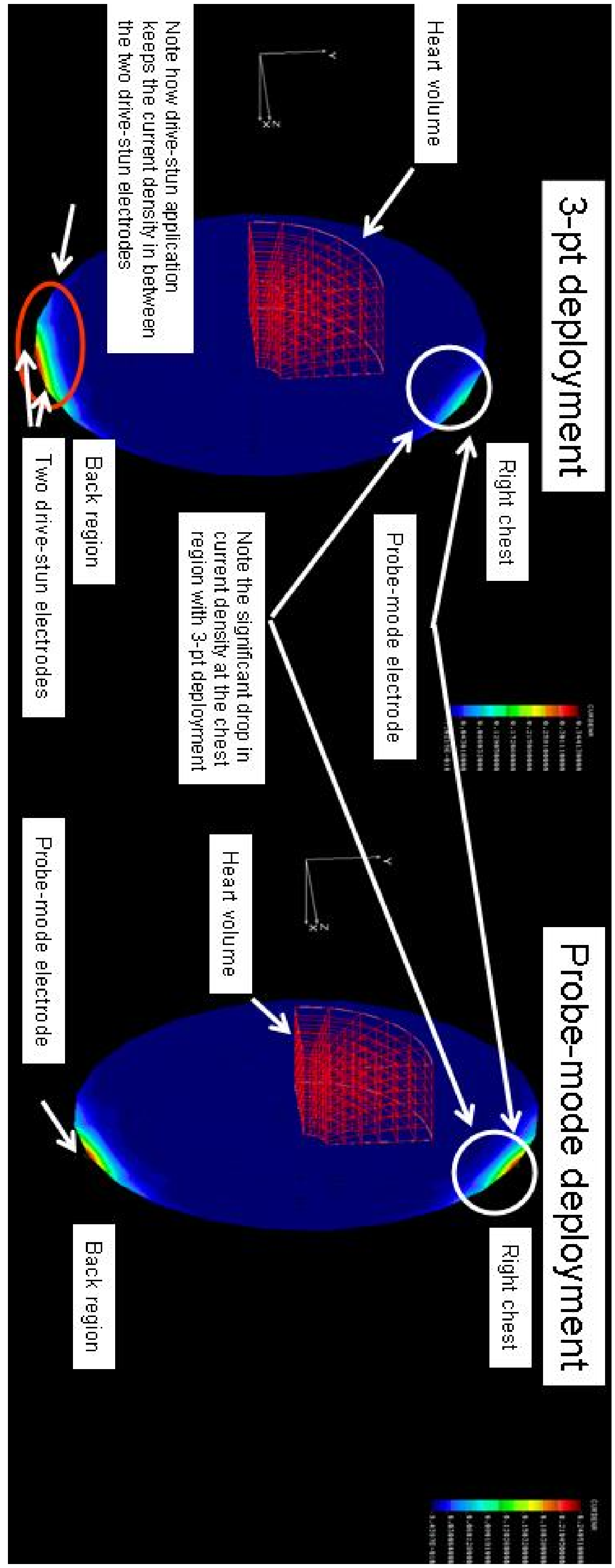

Fig. 6. Cross-sectional current density theoretical distributions by a TASER M26 deployed in 3-point mode vs. probe-mode. With electrodes in 3-pt deployment more than 50% of the current is diverted away from deeper body tissues. A significant percentage of current is shunted between the two drive-stun electrodes.

Table III. Summary of theoretical estimates for field strength, current density and safety margins for the two placements.

Configuration	E field [V/m]	Crt. density [mA/cm^2]	Safety margin – cardiac capture	Safety margin – VF	Safety margin – phrenic/vagus nerve capture (respiratory arrest)	Safety margin – skeletal muscle electroporation
3-point	0.27	0.59	576	1689	15	15195
Probe-mode	0.39	0.85	156	996	4	4103

IV. CONCLUSIONS

TASER CEW cartridges carry drive-stun electrodes on them. However, per cartridge specifications, these electrodes are recessed, not even with the cartridge surface [3]. Therefore, it is expected that these drive-stun electrodes carried on the cartridge would not make perfect electrical contact to the suspect's body when the cartridge is pressed against the suspect. The analyses above are limited in the sense that we considered perfect electrical contact made by these drive-stun cartridge electrodes. Accounting for the recessed drive-stun electrodes carried by cartridges, the safety margins associated with 3-point deployment would be theoretically expected to be even higher.

Per theoretical analyses above, we conclude that TASER CEWs are highly likely to be safe when deployed in a 3-point mode. Our previous studies have shown high theoretically estimated safety margins for the drive-stun and probe-mode deployments. With any FEM there are intrinsic inaccuracies associated with estimating actual current flow. Such inaccuracies are typically low and may be caused by the selection of material properties, the location of boundary conditions, the resolution of the FEM, etc. Given that all TASER CEW safety margins numerically estimated above and in previous studies are very large numbers, they mitigate the effects of intrinsic FEM inaccuracies. Even after any reasonable adjustments made to address variations in material properties, location of boundary conditions or the limited resolution of FEMs, the estimated safety margins above still remain high. Consequently, the 3-point mode deployment is expected to be at least as safe as the drive-stun and probe-mode deployments.

V. REFERENCES

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