

New Conducted Electrical Weapons: Electrical Safety Relative to Relevant Standards

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Introduction: We have previously published about TASER® conducted electrical weapons (CEW) compliance with international standards. CEWs deliver electrical pulses that can inhibit a person's neuromuscular control or temporarily incapacitate. An experimental Rotating-Field (XRF) waveform CEW and the X2 CEW are new 2-shot electrical weapon models designed to target a precise amount of delivered charge per pulse. They both can deploy 1 or 2 dart pairs, delivered by 2 separate cartridges. Additionally, the XRF controls delivery of incapacitating pulses over 4 field vectors, in a rotating sequence. As in our previous study, we were motivated by the need to understand the cardiac safety profile of these new CEWs. The goal of this paper is to analyze the nominal electrical outputs of TASER XRF and X2 CEWs in reference to provisions of all relevant international standards that specify safety requirements for electrical medical devices and electrical fences. Although these standards do not specifically mention CEWs, they are the closest electrical safety standards and hence give very relevant guidance.

Methods: The outputs of several TASER XRF and X2 CEWs were measured under normal operating conditions. The measurements were compared against manufacturer specifications. CEWs electrical output parameters were reviewed against relevant safety requirements of UL 69, IEC 60335-2-76 Ed 2.1, IEC 60479-1, IEC 60479-2, AS/NZS 60479.1, AS/NZS 60479.2, IEC 60601-1 and BS EN 60601-1.

Results and Conclusion: Our study confirmed that the nominal electrical outputs of TASER XRF and X2 CEWs lie within safety bounds specified by relevant standards.

Keywords—Cardiac, CEW, Fibrillation, Safety, Standards, TASER.

I. INTRODUCTION

The conducted electrical weapon (CEW) is a less-lethal law enforcement, military, and civilian force option. These weapons, such as TASER® CEWs, deliver trains of low-charge, very short duration electrical pulses designed to temporarily inhibit a person's neuromuscular control through motor-nerve mediated neuromuscular activation. We have previously published about CEW operation, performance and safety [1].

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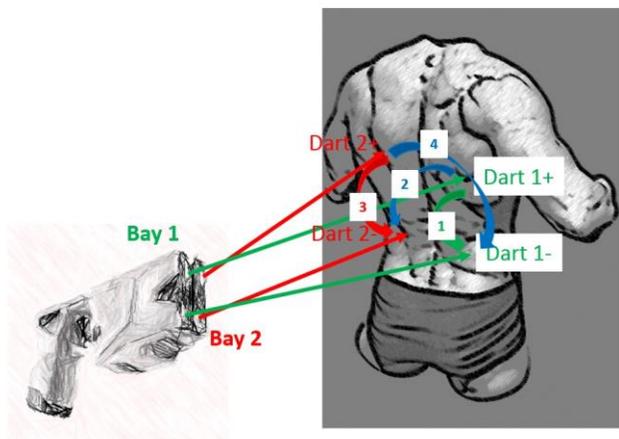
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A previous Expert Panel report stated “Because the electrical characteristics and outputs of CEW devices are variable and evolving, each CEW device must be tested on its own merit to assess performance as well as the ability to induce neuromuscular incapacitation and adverse physiological and health effects.” Similarly each CEW waveform must be tested on its own merits in regard to relevant safety standards [2].

We focused on analyzing the performance of 2 new next generation “Smart-Weapon” CEWs, the eXperimental Rotating-Field (XRF) waveform and the X2 CEWs [3, 4]. In conducting the study, we referred to relevant electrical safety standards [5 – 12]. Earlier production samples of the X2 CEW were analyzed in our previous publication [1]. This study analyzes the most recent X2 CEW. Both the XRF and X2 CEWs target a precise amount of delivered charge per pulse. They use electronic circuits to measure the charge delivered by the previous pulse. The targeted charge delivery of the next pulse is then controlled accordingly so that it is tightly adjusted toward the specified charge value. Both CEWs use 2 cartridge bays in order to provide for immediate back-up shots. The XRF drives electrical stimuli along 4 field vectors in a rotating sequence, as shown in Fig. 1. The dart numbers correspond to the cartridge bay number. First pulse of the sequence is delivered between darts 1+ and 1-. Second pulse of the sequence goes from dart 1+ to dart 2-. Third pulse is applied between darts 2+ and 2-. Fourth pulse crosses from dart 2+ to dart 1-. Then the sequence repeats itself. There are 11 pulses per second (pps) delivered across each of the 4 vectors. Hence, under normal operation, each dart fires at a rate of 22 pps.

Figure 1. Rotating pulse-drive sequence for the XRF CEW (figure shows an illustration of a CEW, not the actual XRF CEW).



The rotating pulse-drive sequence is designed to increase the efficacy of the XRF weapon. Even when XRF is deployed from a closer distance to a subject, the cross vectors #2 (darts 1+ to 2-) and #4 (darts 2+ to 1-) are likely to have a dart spread greater than 30 cm, a distance which has been empirically found to produce a more efficacious motor-nerve mediated muscular lock-up [13].

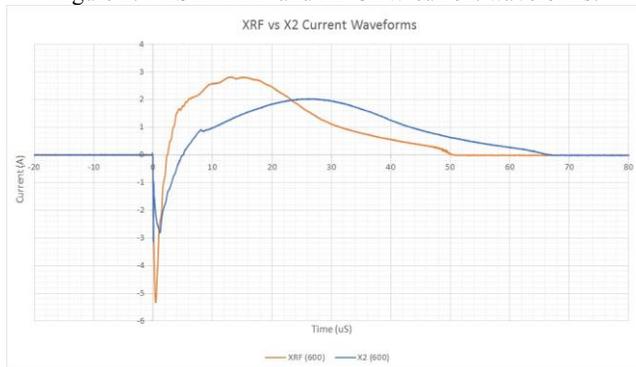
Table I provides a summary of measured electrical output parameters and other factors for these CEWs. A 600 Ω non-inductive load was connected to the device output. Their typical output current and voltage waveforms are shown in Figs. 2 and 3, respectively. The nominal TASER XRF and X2 normal-operation electrical output parameters were reviewed against relevant safety requirements of UL 69, IEC 60335-2-76 Ed 2.1, IEC 60479-1, IEC 60479-2, AS/NZS 60479.1, AS/NZS 60479.2, IEC 60601-1 and BS EN 60601-1 [5 – 12].

TABLE I. Output parameters of TASER XRF and X2 CEWs.

Parameter	XRF	X2
Open-circuit peak voltage [kV]	50	52
Pulse voltage (main phase) [V]	770	560
Peak Main Phase voltage in typical load [kV]	1.7	1.2
Peak Main Phase current in typical load [A]	2.8	2
Energy delivered in typical load [J/pulse]	0.098	0.069
Power into 600 ohm load [W]	2.15	1.3
Net charge in the main phase [μC]	64	62
Impulse duration [μs]	50	66
Pulse rate [pulse/s]	22	19
Aggregate average current (net charge*pps) [mA]	1.4	1.2
Total delivery duration [s]	5	5
On-demand delivery termination	Yes	Yes
Charge metering	Yes	Yes
Smart Probes	Yes	Yes
Integrated EVIDENCE.com	Yes	Yes
Trilogy Logs (pulse, event, and engineering logs)	Yes	Yes
Optional Auto Shut-Down Performance Power Magazine (APPM)	Yes	Yes

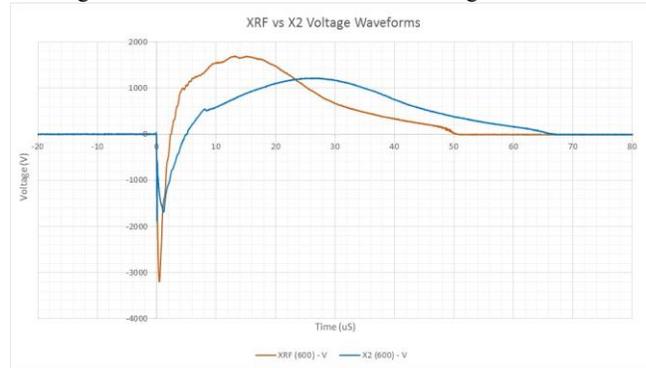
The UL 69 requirements cover electric-fence controllers used only for the control of animals [5]. The IEC 60335-2-76 Ed 2.1: 2006 standard deals with the safety of electric-fence energizers and with means by which wires in agricultural, domestic or feral animal-control fences may be electrified or monitored [6].

Figure 2. TASER XRF and X2 CEW current waveforms.



Standards IEC 60479-1, IEC 60479-2, AS/NZS 60479.1, AS/NZS 60479.2 describe effects of electrical current on human beings and livestock [7 – 10]. The 60479-1 series (IEC or AS/NZS) describes the effects of DC and sinusoidal alternating currents with frequencies between 15 Hz and 100 Hz passing through the human body [7, 9]. The effects of non-sinusoidal currents of higher frequencies are covered by the 60479-2 series (IEC or AS/NZS) [8, 10].

Figure 3. TASER XRF and X2 CEW voltage waveforms



The IEC 60601-1 standard stipulates accepted regulatory requirements for the safety of electrical medical devices [11]. The corresponding European Norm (EN) version has similar scope and requirements [12]. As published previously, our testing and analysis methodology was consistent with CEW testing performed by others [14 – 21].

II. METHODS

1. Underwriters Laboratories (UL) Standard for Electric-Fence Controllers, UL 69 10th Ed, 2009.

Requirements of earlier UL 69 editions are consistent with those cited in the 2009 Edition [5]. UL 69 also covers portable and permanently mounted electric-fence controllers with peak-discharge or sinusoidal-discharge output for indoor or outdoor use, including battery-operated controllers intended to operate from battery circuits of 42.4 V or less, line-operated controllers, combination controllers intended to operate from either a battery or a line circuit, and photovoltaic module battery operated controllers. These requirements do not cover electric-fence controllers for the continuous (uninterrupted) current type or intermediate equipment, such as a converter, a rectifier, or the like, that is sometimes used between the primary source of supply and an electric-fence controller and that is investigated only as part of a complete controller.

The UL 69 standard load consists of a non-inductive 500 Ω resistor with an adjustable parallel capacitor of $\leq 2 \mu\text{F}$ adjusted for maximum output. The capacitor can be neglected for our purposes as it consistently lowers outputs with the short XRF and X2 pulse. At 2 μF capacitive loading, their peak main-phase voltages drop from over 1000 V to only about 30 V. In order to assess worst case scenarios, we evaluated the waveforms shown in Figs. 2 and 3, without using a capacitive load.

In its Fig. 22.1, the standard shows the relationship between current (mA) versus impulse duration (ms) (see Fig. 4 for details). UL 69 defines the impulse duration as the interval of time which contains 95% of the overall energy. The 95%-energy durations for XRF and X2 are 30 μ s and 44 μ s, respectively. The equation indicating this relationship is:

$$\text{Current (mA)} = 2000 \times (\text{Duration (ms)})^{-0.7}$$

For impulse with a duration of 0.03 ms (XRF) and 0.044 ms (X2), the equation yields:

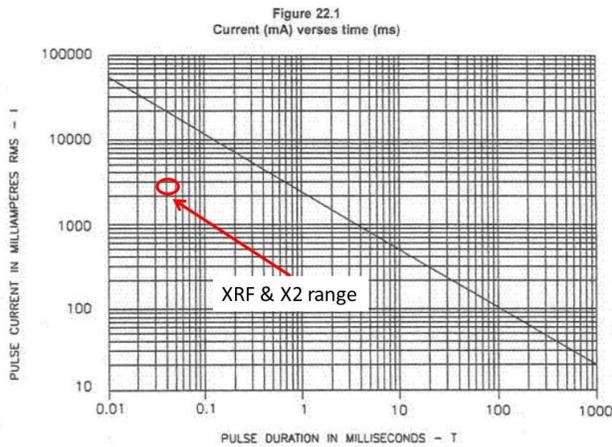
$$I_{\text{impulse_UL_limit_XRF}} = 23\,283 \text{ mA}_{\text{rms}}$$

$$I_{\text{impulse_UL_limit_X2}} = 17\,807 \text{ mA}_{\text{rms}}$$

Abnormal, rapid-fire, operation restrictions are specified as:

$$\text{Current (mA)} = 2000 \times (\text{Duration (ms)})^{-0.7} \times (\text{pps})^{-0.5}$$

Figure 4. UL 69: Current vs. impulse duration graph.



The variable *pps* represents the pulse repetition rate, expressed in pulses per second (pps). Section 23.2.3 of the standard specifies these restrictions when the interval between adjacent pulses drops below 0.75 s and requires that the device shall interrupt the output within 3 min. Both XRF and X2 automatically interrupt output after 5 s. Utilization of the optional Auto Shut-Down Performance Power Magazine (APPM) prevents the CEW trigger from being held back continuing discharge and requires reactivation of the trigger to reinitiate discharge. For impulse durations of 0.03 ms (XRF) and 0.044 ms (X2) and for repetition rates of 22 pps (XRF) and 19 pps (X2):

$$I_{\text{repetitive_UL_limit_XRF}} = 4\,964 \text{ mA}_{\text{rms}}$$

$$I_{\text{repetitive_UL_limit_X2}} = 4\,085 \text{ mA}_{\text{rms}}$$

2. IEC 60335-2-76, Ed 2.1: Household and Similar Electrical Appliances—Safety—Part 2—76: Particular Requirements for Electric Fence Energizers, 2006.

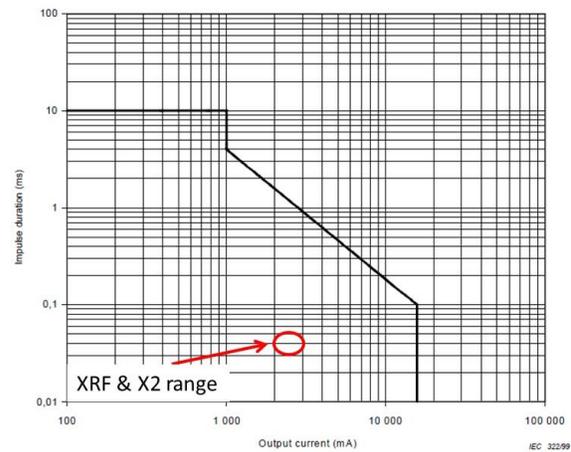
In section 3.118, the standard defines “standard load [6]:

load consisting of a non-inductive resistor of $500 \pm 2.5 \Omega$ resistor.”

In section 22.108, the standard calls out that an energizer output characteristic shall be such that (see Fig. 5 for details) [6]:

- The pulse repetition rate shall not exceed 1 Hz;
- The duration of the impulse shall not exceed 10 ms;
- For energy-limited energizers, the energy/pulse in the 500 Ω load shall not exceed 5 J/pulse;
- For current-limited energizers the output current in the standard load shall not exceed 15,700 mA_{rms} for impulse duration of not greater than 0.1 ms;
- If the pulse repetition rate becomes greater than 1.34 Hz (rapid fire), the discharge energy per second into a load consisting of a non-inductive resistor of 500 Ω shall not exceed 2.5 J/s (i.e. 2.5 W) for a period not exceeding 3 min, within which the device shall interrupt its output.

Figure 5. IEC 60335-2-76: Impulse duration vs. output current.



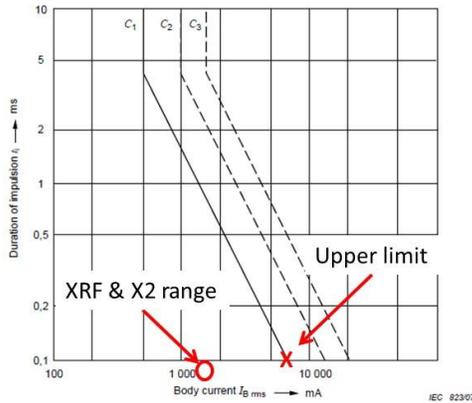
NOTE The equation of the line relating impulse duration (ms) to output current (mA) for 1 000 mA < output current < 15 700 mA, is given by impulse duration = $41,885 \times 10^3 \times (\text{output current})^{-1.34}$

3. IEC 60479-1 & -2: Effects of Current on Human Beings and Livestock, General & Special Aspects, 2005 – 2007.

The IEC 60479 standard deals with effects of electrical current on human beings and livestock [7 – 10]. IEC 60479-1 describes the effects of sinusoidal alternating currents with frequencies between 15 Hz and 100 Hz and of direct currents passing through the human body, respectively [7, 9]. The effects of non-sinusoidal currents of higher frequencies are covered by IEC 60479-2 [8, 10]. Section 11.4 of IEC 60479-2 describes the thresholds of ventricular fibrillation (VF) for impulses of short duration. It states that “for 50% probability of fibrillation, *F_q* is of the order of 0.005 As (i.e. 5 mC).” *F_q* is defined as the charge of the impulse. Figure 20 of section 11.4 of IEC 60479-2 describes requirements for region C1, which the standard lists as “no fibrillation” (shown in Fig. 6). Section 11.2.2 and Fig. 18 of IEC 60479-2 define *I_{Brms}* as being $I_{\text{peak}}/\sqrt{6}$ for currents approximated as being mostly unidirectional impulses of short durations.

The requirements of standards AS/NZS 60479.1 and AS/NZS 60479.2 are similar to those of the corresponding IEC versions, IEC 60479-1 and IEC 60479-2 [9, 10].

Figure 6. IEC 60479-2: Risks of ventricular fibrillation.



The curves indicate the probability of fibrillation risk for current flowing through the body from the left hand to both feet. For other current paths, see 5.9 in IEC 60479-1.

- Below C_1 : no fibrillation;
- Above C_1 up to C_2 : low risk of fibrillation (up to 5% of probability);
- Above C_2 up to C_3 : average risk of fibrillation (up to 50% of probability);
- Above C_3 : high risk of fibrillation (more than 50% probability).

4. *IEC 60601-1: Medical electrical equipment. General requirements for basic safety and essential performance. 2005, including corrigenda up to August 2012.*

The 60601-1 international standards stipulate accepted regulatory requirements for the safety of electrical medical devices [11, 12]. Among many other requirements, the standard also sets the allowed threshold for the patient leakage current for medical devices that have direct contact to patients' heart. Citing from the standard, we learn that:

“The allowable value of PATIENT LEAKAGE CURRENT for TYPE CF APPLIED PARTS in NORMAL CONDITION is 10 μ A which has a probability of 0.002 for causing ventricular fibrillation or pump failure when applied through small areas to an intracardiac site.

Even with zero current, it has been observed that mechanical irritation can produce ventricular fibrillation. A limit of 10 μ A is readily achievable and does not significantly increase the risk of ventricular fibrillation during intracardiac procedures.”

While the 10 μ A_{rms} limit does not apply to TASER XRF or X2 CEWs, as they are not medical devices and do not deliver an intracardiac charge, the rationale behind the 0.002 probability of VF induction is relevant to CEW applications. Although a 10 μ A_{rms} CF patient-leakage current is deemed to have a 0.002 probability (1 out of 500) of causing VF or pump failure in humans, the standard accepts this value as being safe. Regulatory agencies, such as the United States (US) Food and Drug Administration (FDA) or the Germany-based Technischer Überwachungs-Verein (TUV), certify electrical medical devices as being safe for use in intracardiac clinical procedures

if they comply with this patient leakage current limit. Intracardiac procedures carry the highest risk for patients. Therefore, by accepting requirements of IEC 60601-1, or the equivalent BS EN 60601-1, these regulatory agencies accept that a 0.002 probability of causing VF represents an extremely low risk.

III. RESULTS

1. *Underwriters Laboratories (UL) Standard for Electric-Fence Controllers, UL 69 10th Ed, 2009.*

Table II presents relevant output parameters of the TASER XRF and X2 CEWs with respect to previously discussed requirements of UL 69. Comparatively, the XRF and X2 CEW output range is also illustrated in Fig. 4.

TABLE II. XRF and X2 CEWs vs. UL 69 limits.

	XRF CEW	X2 CEW
Duration [ms] (at 95% of impulse energy)	30 μ s	44 μ s
UL limit I _{impulse_UL_limit}	23283 mA _{rms}	17807 mA _{rms}
Measured main-phase I _{impulse_max}	2830 mA	2030 mA
UL limit I _{repetitive_UL_limit}	4964 mA _{rms}	4085 mA _{rms}
Measured I _{repetitive_rms}	2265 mA _{rms}	1564 mA _{rms}

2. *IEC 60335-2-76, Ed 2.1: Household and Similar Electrical Appliances—Safety—Part 2—76: Particular Requirements for Electric Fence Energizers, 2006.*

Table III presents relevant output parameters of the XRF and X2 CEWs with respect to previously discussed requirements of IEC 60335-2-76, Ed 2.1. Comparatively, the XRF and X2 CEW output range is also illustrated in Fig. 5. Both CEWs deliver far less energy per pulse than the 5 J/pulse limit required by the standard, 0.098 J/pulse and 0.069 J/pulse, respectively. Based on the 95% of energy duration, the energy/second levels for the XRF and X2 CEWs are 0.093 J * 22 pps = 2.04 J/s and 0.065 J * 19 pps = 1.24 J/s, respectively.

TABLE III. XRF and X2 CEWs vs. IEC 60335-2-76 limits.

	XRF CEW	X2 CEW
Duration [ms] (at 95% of impulse energy)	30 μ s	44 μ s
IEC limit I _{impulse_IEC_limit}	15,700 mA _{rms}	15,700 mA _{rms}
Measured main-phase I _{impulse_max}	2830 mA	2030 mA
IEC limit Energy _{repetitive_IEC_limit}	2.5 J/s	2.5 J/s
Measured Energy _{repetitive}	2.04 J/s	1.24 J/s

3. *IEC 60479-1 & -2: Effects of Current on Human Beings and Livestock, General & Special Aspects, 2005 – 2007.*

The main phase net charge of XRF and X2 CEWs was measured to be 64 μC and 63 μC , respectively. These values are at least 50 times lower than the threshold indicated by IEC 60479-2 for a 50% probability of VF induction. Even if considering I_{Brms} equal to the peak main phase output current of the XRF and X2, 2.8 A and 2 A, the output operating point continues to fall within the “no fibrillation” region C1 (Fig. 6). But, as explained above, the actual I_{Brms} can be approximated as $2.8 \text{ A}/\sqrt{6}$ and $2 \text{ A}/\sqrt{6}$ or 1.14 A and 0.82 A, for the XRF and X2 CEWs, respectively. At impulse durations of 0.05 ms, for the XRF, or 0.066 ms, for the X2, IEC 60479-2 specifies the limit of the C1 region at approximately 6 A (XRF and X2 CEW output range shown in Fig. 6 for comparison). Consequently, the electrical parameters of XRF and X2 CEWs are well within the “no fibrillation” region C1, as specified by IEC 60479-2. Even the peak electrical currents delivered by XRF and X2 CEWs during their arc phases (5.3 A and 3.1 A, respectively) fall in the “no fibrillation” region C1. For clarification, when delivered to a 600 Ω load for a full 5 s cycle, the actual root-mean-squared (RMS) value of the output current of a XRF CEW was measured at 60 mA_{rms} . Similarly, for a full 5 s cycle, the X2 CEW the output current RMS value was 47 mA_{rms} . Thus, according to the IEC 60479-2 criteria, an impulse from a XRF or X2 CEW has very remote chances, if any, of directly inducing VF in a human. With a sequence of pulses, the VF threshold may decrease (see section 9.2 of IEC 60479-2) [8, 10]. Example 1, shown in Fig. 14 section 9.2.2, page 26, discusses the VF risk of a train of 4 very short current pulses, similar to those put out by TASER CEWs. The IEC 60479-2 concludes that “the risk of ventricular fibrillation in this case could be considered low [8].” In light of this Example, considering the narrow impulse duration (50 μs and 66 μs) and short duty cycle (< 0.2%) of XRF and X2 CEWs, the IEC 60479-2 standard confirms that a series of pulses delivered by these CEWs would not increase the risk of VF relative to that associated with one impulse.

We conclude that the XRF and X2 CEWs electrical outputs are within the “no fibrillation” region, as defined by IEC 60479-2.

4. *IEC 60601-1: Medical electrical equipment. General requirements for basic safety and essential performance. 2005, including corrigenda up to August 2012.*

By accepting IEC 60601-1, or the equivalent BS EN 60601-1, regulatory agencies accept that a 0.002 probability of causing VF, or of 1 in 500 events, represents an extremely low risk. The reported theoretical VF risk with CEWs is much lower. Between 2011 and 2016, there were approximately 180,000 X2 CEWs sold in the United States [4]. At the time of this article, the XRF CEW has not yet been released. Previous statistics gathered from the field use of TASER CEWs show an

average of 0.55 field uses/year/sold CEW [22]. Hence, we estimated that, to-date, there have been approximately 235,000 field uses of Smart-Weapon CEWs. None of these have been confirmed to result in cardiac arrest. While, at this time, the field use numbers are too low to support statistically significant conclusions, the trend is supportive and consistent with a very high safety profile of better than 0.0000043. At least preliminarily, the observed safety risk of Smart-Weapon CEWs (i.e. less than 0.0000043) is at least 470 times smaller than the IEC 60601-1-accepted VF risk of 0.002.

IV. DISCUSSION

The relevant sections of all standards discussed above reflect electrical requirements concerning cardiac safety of subjects exposed to CEW currents. Indicative of the importance of this topic, others have studied it as well.

Nimunkar and Webster also determined that the X26 CEW electrical parameters fall within relevant safety limits of UL, IEC and AS/NZS standards and within those of a new proposed electrical standard for testing the safety of pulsed electric devices [20]. Adler et al. described a detailed methodology for testing TASER CEWs [21]. Their protocol was based on experience of testing 6000 TASER CEWs in affiliated labs. They referenced the IEC 60479-2 electrical safety standard [8] and used it to compare the measured TASER CEW electrical output parameters. According to their results, even after accounting for device-to-device variability, the measured TASER CEW output parameters fell well within the safety limits prescribed by IEC 60479-2 [21].

The relevance of these results and findings is that CEWs which meet safety requirements of the standards discussed above are more likely to exhibit a low risk of inducing fatal cardiac conditions. Other standards, such as ICNIRP, IEEE, FCC, may be important as well [23 – 25]. However, such standards focus more of radiofrequency absorption by human body, electromagnetic compatibility or immunity, or on effects of electromagnetic fields on the human body, rather than on cardiac safety of pulsed electric devices. For example, Table 1 of ANSI/IEEE C95.1 – 2005 provides basic restriction to electric field intensity in the heart at frequencies below 5 MHz. Per finite element studies published previously, we believe previous and new CEW models meet these basic restrictions [24, 26]. However, unlike UL, IEC, AS/NZS, EN and BSI standards, the ICNIRP, IEEE, FCC do not provide safety limits that can be tested directly on the output waveform of CEWs. Our future studies will further analyze implications of such standards to use of CEWs.

IV. CONCLUSION

The analyses above focused on the normal-operation performance and safety of the XRF and X2 CEWs in reference to relevant electrical safety standards. In situations when a dart

misses the subject, the XRF CEW rotating pulse-drive sequence shown in Fig. 1 may change. Analyses of such XRF CEW use cases will be reported in our future studies.

Our analyses confirmed that the nominal electrical outputs of TASER XRF and X2 CEWs, when operated under normal conditions, lie within safety bounds specified by relevant requirements of UL, IEC, AS/NZS, EN and BSI, standards.

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