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ORIGINAL PAPER

Benefits, Risks, and Myths of TASER® Handheld Electrical Weapons

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Abstract

Handheld conducted electrical weapons (CEWs) have been used 3.9 million times in the field in 107 countries. Prospective studies (including over 40 k uses of force) find a 65% reduction in subject injuries versus batons, manual control, and "pepper" spray. There is a 2/3 reduction in fatal shootings when CEW usage is not overly restricted. USA-derived data suggest that the temporal subject fatality rate with resistant arrest is ≈ 1:1000 without a CEW and ≈ 1:3000 with the CEW. UK data suggest 85% compliance with simply the threat of a CEW. There have been 18 deaths from falls (16 brain injuries and 2 cervical fractures) and 8 deaths from fume ignition. These 26 deaths provide a fatality risk of 6.7 per million [95% CI 4.5–9.8]. There are 20 cases of unilateral blindness from a probe eye penetration. There were also 4 cases of non-fatal major burns and 1 of permanent brain damage from a fall. These 25 injuries provide a risk of 6.4 per million [(95% CI 4.3–9.5]. The risk of electrocution is very low since present CEWs satisfy the IEC 60335 electric fence limit of 2.5 W and the ANSI-CPLSO-17 limits of 125 μC per pulse with a normalized aggregate current of 2.2 mA. Arrest-related death anecdotes alleging an electrocution all fail several diagnostic tests for an electrocution. While reducing subject injury and death by about 2/3, CEW usage has an overall major complication rate of 13.1 per million field uses [95% CI 9.9–17.2], primarily from falls, fires, and eye injuries.

Keywords ARD · Arrests · CEW · Electrical weapon · Force · TASER®

Introduction

The majority of handheld conducted electrical weapons (CEWs) are the TASER® brand manufactured by Axon Enterprise, Inc., formerly TASER International, Inc., and therefore the vast majority of the peer-reviewed publications are based on this brand. Other probe-launching brands include the PhaZZer Enforcer, Condor Spark, Jiun An Raysun X-1, and the Karbon Arms Stinger [1–6]. Unless otherwise mentioned, the papers discussed refer to TASER brand weapons.

In probe mode, the TASER® handheld CEW uses compressed nitrogen to deploy 2 small probes at typical distances of up to 7.7 m [7, 8]. Some cartridge models can reach a distance of 11 m. When the CEW trigger is pulled, the high voltage pulse first serves to activate a primer cartridge to release the nitrogen to propel the probes toward the target. These probes are designed to pierce or become lodged in most light clothing (and to complete the circuit with the 50-kV arcing capability). The sharp (dart) portion of the probe is 9–13 mm long and will typically penetrates the epidermis and dermis to a depth of ≈ 6 mm for a good electrical connection.

The ultra-short duration (50–100 μs) electrical pulses applied by TASER CEWs are intended to stimulate Type A-α motor neurons between, and in close proximity to, the probes, which are the nerves that control skeletal muscle contraction. This typically leads to a loss of regional muscle control and a fall to the ground to end a violent confrontation or suicide attempt, or to facilitate capture or

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control. There is a common misunderstanding that the CEW induces a powerful tetanic muscle contraction [9]. In fact, the primary effect is to deny the subject regional muscle control and the resulting contraction has been estimated at 46% of a person's normal maximum voluntary contraction [10]. This effect also ceases immediately after the current stops thus allowing a rational subject to comply with officer instructions [11]. The probe-mode application also provides pain, as do all less-lethal force options, but that is not central to its operation. The pain is also usually irrelevant since 80% of less-lethal force recipient subjects are largely analgesed by illegal drugs, alcohol, or psychotic break [12, 13].

Alternatively, the CEW may be used in a "drive-(contact or touch) stun" mode by pushing the front of the weapon into the skin to function as a higher charge contact stun gun. With the fixed electrodes, only ≈ 4 cm apart—and the lack of skin penetration—the current flow is primarily through the dermis and fat layer between the electrodes and there is no significant penetration beyond the subdermal (or subcutaneous) fat layer. See Fig. 1. Since there is insufficient depth of current flow to capture muscles, the drive-stun mode serves only as a pain-compliance technique.

There are no known significant complications with drive stuns. The American Academy of Emergency Medicine has the following guideline on drive-stun applications [14]:.

> For patients who have undergone drive stun or touch stun … exposure, medical screening should focus on local skin effects at the exposure site, which may include local skin irritation or minor contact burns. This recommendation is based on a literature review in which thousands of volunteers and individuals in police custody have had drive stun … used with no untoward effects beyond local skin effects.

Primary Benefits

Accountability

Modern CEWs provide a unique force option because they have extensive objective operation, discharge, application, and engineering documentation and accountability data-recording mechanisms. No other force option has such objective incident documenting capabilities. For example, there is no permanent record of the number and velocity of baton strikes, whereas each CEW trigger pull is recorded along with the charge of each pulse for models developed by the primary manufacturer since 2009.

CEW-Presentation Compliance

A surprising benefit of CEWs is the ability to obtain subject compliance with just the threat of the weapon without discharging a probe or applying a drive-stun contact. This begins with mere display and can progress to arming (which turns on the light and LASER pointer), to arcing. During 2018, the CEW was used in 17,000 incidents in England and Wales [15] In 15,000 (85%) of these incidents, the subject was not exposed to electrical discharge of the weapon. Note that a non-contact arcing display is not considered a discharge. Similarly, in Queensland, Australia, in 835 CEW uses, 75% were presentation only [16].

Slightly less dramatic but similar results are seen in North America. In 16 Canadian reports (12 agencies) from 2006 to 2009, there were 1.14 ± 1.09 brandishing and arcing uses for every discharge with a weighted average of 1.55 per discharge. In 37 US reports (30 agencies) from 2005 to 2009, there were 1.64 ± 1.32 brandishing and arcing uses for every discharge with a weighted average of 1.71 per discharge. The overall North American experience covered 6378 uses of which 62.7% were non-discharge [17]. Other force options have only minor presentation (non-use) subject compliance capabilities [18].

Voluntary-Muscle Override Capability

A primary benefit of probe-mode CEW (but not drive-stun) applications that no other intermediate-force option possesses is the ability to induce neuromuscular incapacitation (NMI) thereby overriding voluntary muscle control. All force options other than CEWs gain subject compliance by: (1) causing sufficient pain or discomfort to compel submission, or (2) cause sufficient physical trauma to induce submission. This particular feature of the CEW is especially recommended for facilitating capture, control, and restraint, and often delivery of the individuals with mental disturbance to medical personnel. Numerous book chapters and papers dealing with interactions with agitated or aggressive subjects recommend broad probe-spread CEW deployments to gain rapid control [19, 20].

Injury Reduction

Subject injury rates are significantly lower with the adoption of the CEW. The MacDonald study covered 12 US law enforcement agencies and 24,380 uses of force [21]. They found that the CEW reduced subject injury by 65%. Taylor et al. analyzed data from 13 US agencies including 16,918 uses of force and described a reduction in injuries requiring medical attention of 75% [22]. Numerous other studies have documented similar reductions in subject injury rates [8, 23–28].

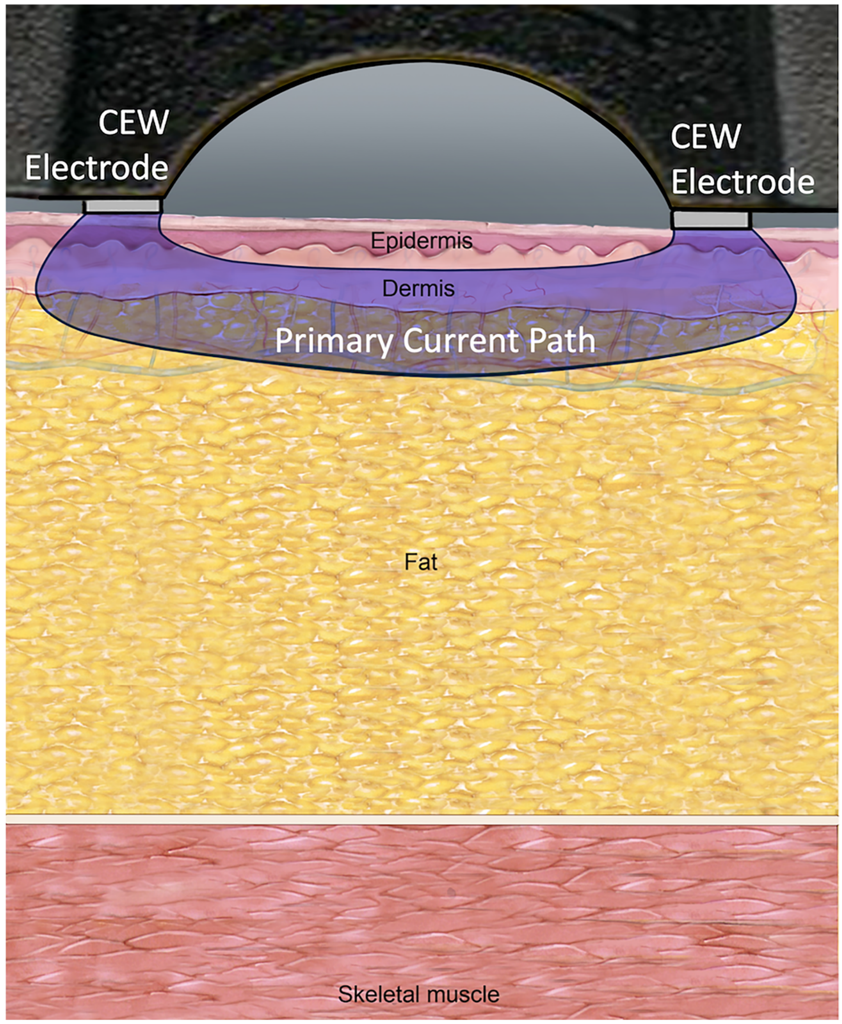

Fig. 1 The majority of the drive-stun current is confined to the fat and dermis layer

Bozeman performed a prospective non-randomized study of various force options covering 893 uses of force [29]. A panel of 5 physician investigators graded injury severity. Significant injuries were found in 10.6% of canine uses [95% CI 4.2–23.0%], 0.85% of unarmed physical force [CI 0.3–1.9%], and 0% of 504 CEW uses [CI 0–0.9%]. The rate of significant canine injury was statistically consistent with the 4.8% rate of hospital treatment found by Hickey [30]. The rate of significant CEW injury was statistically consistent with the 0.25% rate [95% CI 0.1–0.7%] previously reported by Bozeman [31].

There are 2 outliers in the literature. Terrill reported higher levels of subject injuries but this paper included probe punctures as injuries [32]. This definition could be criticized since 0.8-mm skin punctures are similar in size to puncture wounds for vaccinations, blood tests, and intravenous access [33]. Ba et al. reported no decrease in subject injuries but the definition of injury was left to police officers rather than medical personnel with no gradation of injury levels. The authors accepted that they did not know how often probe injuries were counted in their data [34].

Mortality Reduction

The non-firearm ARD (arrest-related death) rate, temporal to law enforcement force interactions, is generally estimated to be around 1:1000 [35]. Karch calculated a fairly consistent rate of 1:1234 using US data from 2003 to 2005 [36–38]. A comprehensive search, of media and legal databases, could only find 1081 *residual* ARDs in the USA since the inception of the CEW to date [39]. The USA had 83.6% of annual reported CEW discharges in 2010 providing an estimate of 3.26 million total US discharges to date (and 3.9 million worldwide). This gives an ARD CEW temporal—not causal–mortality rate of about 1:3017. Thus, the CEW reduced all-cause mortality by about 66% compared with the classical estimate and 59% compared with Karch's estimate. The reduction in non-firearm ARDs is consistent with the 2/3 reduction in firearm fatalities in agencies where CEW usage was not overly restricted [40]. That, in turn, is supported by the prospective Eastman study finding that 5.4% of CEW uses replaced lethal force [41].

Complications

Eye Penetrations

A CEW has both LASER targeting and fixed sights. The X26(E) CEW series has a single LASER that approximately aligns with the top probe. The lower probe is launched at a separation angle of 8° below the LASER line. To obtain a high level of motor-nerve-mediated NMI, there must be a probe separation of at least 30 cm on the front of the body [42]. This requirement, of a large spread, adds to a risk of a probe contacting the face, especially if the subject ducks to "avoid" the probes.

Globe rupture can be expected ($p = 0.5$) when the eye is within 6 m of the CEW muzzle and decreases with an increasing distance [43]. Some of the penetrating eye injuries involve only a perforation by the dart portion of the probe. As of 2017, there had been 29 reported penetrating eye injuries out of 3.44 million field uses [44]. The risk of enucleation or unilateral blindness was 69 ± 18%, partial blindness 19 ± 15%, and normal vision after surgical correction 8%. Surgical correction can restore normal vision in some cases. The mean age was 31.1 ± 12.1 years which is consistent with the typical CEW-force recipient (32.0 ± 10.7) [45]. A surprising finding was the 4 accidental CEW deployments resulting in globe penetrations of officers or a family member; there was single case of total blindness. These 4 incidents are not included in the risk statistics as there is no meaningful denominator.

Since the publication of the most recent data concerning eye injuries in 2018, there have been 2 further reports of globe rupture and enucleation. Open media reported the case of a 23-year-old male from New York City, NY, USA, with enucleation. There is also a published case report of a young adult male with successful globe repair and an elective enucleation [46]. Taken together, there have been 20 documented cases of complete unilateral blindness or enucleation giving a risk of 5.1 per million [95% CI 3.3–7.9] by the Wilson score interval.

Fall Injuries

With sufficient probe spread (30 cm in the front or 20 cm in the back), an uncontrolled fall to the ground is likely [42]. The most significant hazard associated with a fall is the possible head impact on the ground that can lead to severe or even life-threatening injuries of the head or neck.

The relationship between the physical parameters of the fall and the risk of life-threatening injuries is very complex and influenced by many factors, such as the form and material properties of the object impacted by the head, the exact fall kinematics, the individual anatomy, and the biomechanical tolerance of various tissues of the person. Forward falls have lower risks of life-threatening injuries compared with backward falls [47]. A severe impact on the face causes fractures (nose, orbitals, and jaw) at moderate force levels resulting in energy absorption and a reduction of the resulting head acceleration similar to the function of crush zones in an automobile body. For backward falls, the higher stability of the occiput region leads to higher accelerations and a higher risk of intracranial injuries (coup and counter-coup contusions with subdural hematoma). The head impact velocity in falls from a standing position can reach values exceeding 6 m/s [47, 48]. Such impact on a non-yielding surface (concrete, stone, or tile) can cause severe or life-threatening injuries even on a flat ground surface.

There have been 16 deaths from traumatic brain injury due to CEW-induced falls [49]. The age of the fatal-fall subjects was 46 ± 14 years which is significantly higher than that of ARDs in general (compared with Ho with 35.7 ± 9.8, $n = 162$, $p = .0002$) [50].

There have been 2 deaths reported from cervical fractures caused by a CEW-induced fall. Overall, we are aware of 18 deaths from falls giving a CEW-induced fall mortality risk of 4.6 per million [95% CI 2.9–7.3]. Bozeman reported 2 non-fatal head injuries from falls—that resolved without neurosurgical intervention or long-term sequelae—out of 1201 CEW uses for a rate of 0.17% [95%CI 0.05–0.61%] [31].

Ignition of Flammable Fumes

Fresh petrol has a lower explosive limit (LEL) of 1.4%. This means that a mixture that is 98.6% air and 1.4% petrol vapor is barely explosive. Surprisingly, this concentration level (1.4%) is not considered acutely toxicologically dangerous but in the "recreational" intoxication range for petrol sniffers [51, 52]. The upper explosive limit (UEL) is 7.6% and thus petrol, per se, is not explosive. The minimum ignition energy (MIE) for

Fig. 2 Probe conducting to cloth over aluminum foil, with arcing in the wire-probe connection eye

Table 1 Relevant flammable substances

Substance	LEL	UPL	MIE (mJ)	Fatal cases	Source or usage
Petrol	1.4%	7.6%	0.24	6	Motor vehicles, arson, suicide, sniffing
Methane	5%	15%	0.21	2	Natural gas
Isobutane	1.8%	9.5%	0.009	0	Spray-paint propellant, lighter fluid
Ethanol	3.3%	19%	0.23	0	Spray-paint propellant, OC spray propellant
Isopropyl alcohol	2%	12%	0.65	0	OC spray propellant
Methyl isobutyl ketone	1%	8%	0.21–0.53	0	OC spray propellant (values are for methyl ethyl ketone)
1,1-DFE	3.7%	18%	UNK	0	Refrigerant aka "dust-off" sniffed recreationally
TATP	NA	NA	NA	0	Explosive

petrol is 0.24 mJ which occurs at the "optimal" concentration roughly midway between the lower and upper limits. This is lower than the ≈ 1 mJ of the popular TASER X26(E) CEW probe-wire connection and thus the fumes are easily ignited by the arc in the "needle-eye" at the back of the probe with an optimal concentration. See Fig. 2.

There are other liquids that have similar explosive capabilities. Benzene (commonly used for methamphetamine production) has a LEL of 1.34%. Butane (often used to manufacture hash oil) has a higher LEL of 1.81–1.86% in different forms. Its isomer, isobutene, is also present in cigarette lighters. Oleoresin capsicum (pepper or OC) aerosol often uses flammable propellants, such as isopropyl alcohol, ethanol, and methyl isobutyl ketone. A few aerosols use nitrogen or other non-flammable propellants, which is inherently non-flammable. Many of the OC aerosols that are labeled as "non-flammable" actually can be ignited by a CEW [53]. Most of these develop a small flame that is unlikely to produce a severe burn injury.

The probes are deployed at an initial velocity of ≈ 43 m/s and the pulse rate is 19–22 pps (pulses-per second). The probes thus travel 2.3 m per pulse. Since the maximum arc is 4 cm, it is unlikely that a probe would ignite a gas by arcing from the probe tip as it approached the subject. The probe-wire arcs are the most likely source of the ignition. While each pulse delivers about 100 mJ of energy to the load, the amount of energy delivered to the arc (in each probe) is estimated at ≈ 1 mJ [54]. However, in the event of heavy or probe-resistant clothing, or a probe lodged in the clothing on the subject's side, there can be an arcing connection with more energy.

The minimum ignition energy for each substance is given in Table 1. The ignition energy increases rapidly for concentrations not centered between the higher and lower explosive limits [55]. This can explain why many electrical weapon

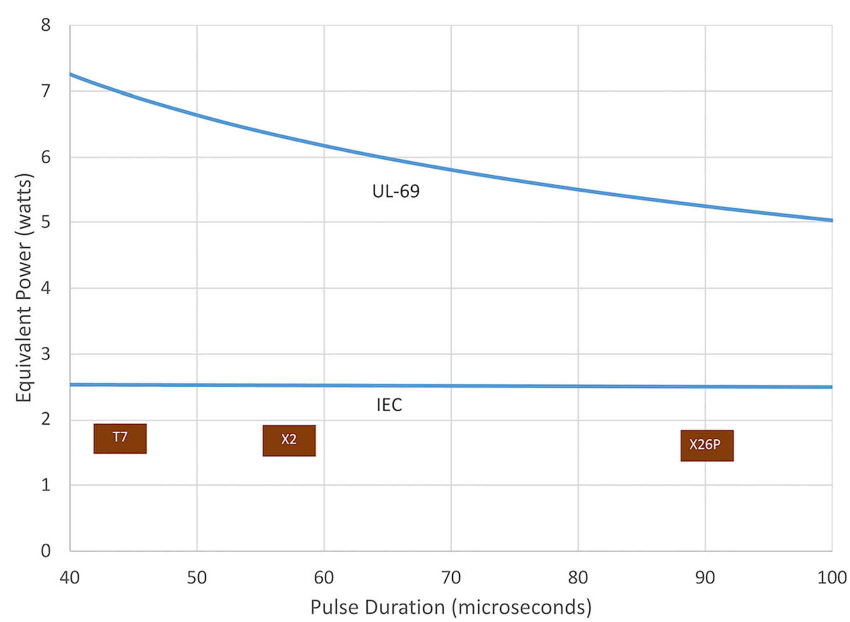

Fig. 3 Electric fence safety standards compared with modern CEWs

probe deployments do not cause an explosion even in the presence of a given fuel.

The published literature reports 6 fatal burns (4 petrol and 2 methane) from CEW ignition [54]. Since that publication, there have been 2 deaths, both of whom had petrol on their clothing in suicide threats (39-year-old male from Texas and a 52-year-old male from Oklahoma). This gives a total of 8 fatal fire deaths out of 3.9 million CEW discharges giving a risk of 2.1 per million [95% CI 1.0–4.0].

Electrocution Myth

The low rate of residual ARDs (of 1:1037) provides strong evidence of the mortality reduction with the CEW. Ironically, some activist groups have suggested that these residual ARDs are electrocutions and caused by the CEW.

Safety Standards

All present TASER brand CEWs deliver less than 2 W which is far less than the 5–7 W allowed by the Underwriters Laboratories (UL) electric fence standard [56], such that CEW-induced electrocution is not expected (Fig. 3). The UL limit depends on the stimulus pulse width and is > 5 W for a 100-μs pulse (applies to the X26P) but 7 W for a 45-μs pulse of the T7. Modern CEWs even satisfy the conservative IEC (International Electrotechnical Commission) and European (Cenelec) 2.5-W limit [57–59]. Were a CEW ever to be proven to have caused death by electrocution, millions of kilometers of electric fences would have to be removed from gardens and agricultural businesses worldwide.

There is also an electrical standard designed specifically for the CEW: ANSI-CPLSO-17. It requires certain minimum outputs for effectiveness and has maximum limits for safety as shown in Table 2. All TASER brand CEWs satisfy this standard.

The typical effects of various AC currents are shown in Table 3. The 1.8 mA of pulsed DC (aggregate) current (for the TASER X2 CEW) is equivalent to 16 mA AC [60]. This level is substantially lower than the 40-mA IEC safety limit used with residual current limiters. Present CEWs thus satisfy all relevant electrical safety standards [61, 62].

A limitation, with applying electrical safety standards, is that they are largely based on *external* skin contact. However, the heart is very close to the skin in the 4th or 5th left parasternal intercostal spaces with a distance as little as 10 mm from the *right* ventricular myocardium to the skin surface in a thin adult [63]. The apex can also be this close but that is less relevant to electrocution since the *left* ventricle (and apex) is much thicker and hence has a higher VF (ventricular fibrillation) threshold [64, 65]. Hence, the electrical safety standards set an upper bound of ≈ 10 mm for the DTH (dart-to-heart distance) for VF induction. Therefore, a probe penetrating the skin directly over the right ventricle could theoretically induce VF even while satisfying these safety standards if the probe was nearly touching the ventricular epicardium. Horowitz found that the induction of VF in humans by right ventricular epicardial bursts required pulse charges of 97 μC (= 24.3 mA × 4 ms) which suggests that the 100 μC TASER X26(E) CEW charge would have to be delivered almost directly to the epicardium [66]. For this reason, the relevant animal and human testing focuses on the critical DTH for the tip of the probe.

Table 2 ANSI-CPLSO-17 output limits

	Raw charge (μC)	Normalized charge (μC)	Pulse rate (Hz)	Normalized aggregate current (mA)
Minimum	40	60	17	1.15
Maximum	125	120	30	2.2

Animal Cardiac Studies

Due to longer QT intervals, shorter repolarization times, and intramural Purkinje fibers, the porcine model's heart is 3 × more electrically sensitive than that of humans [67–70].

Some small swine have had VF induced with a CEW probe very close to the heart. These studies demonstrate that the theoretical risk of electrocution is confined to very small or very thin humans. Walcott et al. showed that swine are 3 times as sensitive to electrical current as humans [71]. The largest swine which was electrocuted by a CEW was reported by Valentino et al. and weighed 36 kg [72]. The levels of dangerous currents scale with body mass just like a drug dosage.

Table 3 AC currents and their typical effects

AC Current (mA)	Effect
1500	Nerve Damage
1000	
500	Cardiac Arrest Probable
200	
100	Cardiac Arrest Possible
50	Interference w Breathing
20	
16	X2 CEW (AC Equivalent)
15	Male No-let-go threshold
10	Muscle Contractions Begin
5	Pain Sensation
1.1	Male Hand Perception
0.7	Female Hand Perception

Color significance: Red is danger, yellow is muscular effects, green is sensation only

Fig. 4 Probability of VF induction vs DTH in swine

Since swine are 3 times as sensitive to electrical current (as humans), we can translate the Valentino 36 kg pig to a 12 kg human. [72] This calculation uses a direct proportion relationship for VF threshold to the body mass. Some authorities argue that the VF threshold scales with the *square root* of body mass [73]. With such a relationship, the Valentino pig is equivalent to a larger 21 kg human. Using this more conservative calculation, the best evidence suggests that the risk of CEW electrocution is limited to humans with a body mass under 21 kg.

Nanthakumar et al. induced VF in 1 of 6 swine weighing 50 kg. However, the swine were given an epinephrine infusion shortly before the CEW exposure, which significantly (but only temporarily for 3–5 min) reduces the VF threshold by up to 26–28% [74, 75]. The DTH or the timing from the start of the epinephrine infusion was not disclosed. By the time officers would arrive to an agitated individual, at least 5 min after a call, the epinephrine actually increases the VF threshold [74, 75].

The required DTH (for VF induction in swine) was studied using spacings of 2–12 mm [76]. They found that the probe tip, through a pre-bored hole to the heart, had to be 5.8 ± 2.0 mm from the epicardium with an X26(E). The return (reference) dart was placed in the inferior part of the abdomen and no myocardium was in a straight vector between the electrodes. This refuted the common misperception that a "transcardiac vector" was relevant to the CEW electrocution risk. Other swine studies have also refuted the transcardiac hypothesis [77]. Lakkireddy et al. also tested close probe spacings to the heart (12–23 mm) without inducing VF with an X26(E), and demonstrating an eightfold safety margin in ≈ 35 kg swine [78, 79]. Wu et al. evaluated probe spacings of 2–12 mm [76]. Based on the Lakkireddy (12–23 mm) and Wu results, the probability of inducing VF (in swine) based upon DTH can be estimated by logistic regression as shown in Fig. 4 [80].

The critical DTH in humans is highly likely to be less than that in swine since swine are more sensitive to external currents inducing VF [81]. This can be quantified as seen in Table 4.

The VFT (VF threshold) ratio column refers to the human VFT being 3 × that of swine and the VFT with maximum catecholamines being 73% of the baseline. The DTH (dart-to-heart) distance ratio refers to the corresponding distance to the heart for inducing VF. For example, the human DTH is 1÷2.41 of the swine DTH and the maximum catecholamines 1÷0.78 (or 1.28x) of that since they temporarily lower the

Table 4 DTH (mm) for VF with X26(E) CEW

Condition	VFT ratio	DTH ratio	DTH mean	DTH st. dev.	Maximum	Notes
Swine	1	1	5.8	2.04	8	Wu-Webster [76].
Human	3.0	2.41	2.41	0.85	3.32	Walcott [71].
With maximum catecholamines	0.73	0.78	3.10	1.09	4.27	Han 26% and Papp 28% VF threshold reduction [74, 75]

Table 5 Human testing with precordial probes and continuous monitoring

Author	*n*	Exposure (s)	Monitoring	Pacing	VF
Stopyra [86]	3*	5	Electrogram	0	0
Dawes [87]	10	5	Echo	0	0
Ho [88]	53	10	Echo	1	0

*Stopyra had 4 subjects but the pacemaker prevented recording in a single case

VFT. The result is an estimated 3.10 ± 1.09 mm for the DTH for VF in a human with maximum catecholamine effect.

A "linear" relationship between the current density and DTH suggests dividing the 5.8-mm swine value by the 3 × swine-to-human sensitivity ratio to get a predicted human DTH of 1.93 mm. However, the current density varies with the distance from the tip (of a percutaneous needle electrode) by a − 5/4 exponent so the correction is slightly smaller [80, 82].

Because of the human anatomy, this is very unlikely in a normal adult but possible in small children. A prospective study of CEW usage in minors (by age) found no complications beyond probe punctures [83]. Risk calculations, using a distribution of body habitus and echo and CT scan data, have been performed [84, 85]. The VF risk is estimated at approximately 1 in 3 million field probe uses.

The primary utility of the swine studies is establishing the critical DTH comparisons between different waveforms and probe configurations. A secondary value is in providing estimate of the lower limits of body mass for safety.

Human Cardiac Clinical Studies

There have been 66 humans monitored continuously during a discharge with precordial CEW probes. See Table 5. There was no VF induction but a single case of asymptomatic cardiac pacing in 2009. That was with an experimental prototype CEW which was never manufactured. However, we are conservatively listing it here.

The margin between cardiac pacing and the induction of VF is quite high and typically about 12:1 [89]. Thus, these clinical data suggest a very low risk of VF induction even with precordial probes.

Since modern CEWs satisfy all relevant electrical safety standards, there have been suggestions of hypotheses for electrocution that do not involve the induction of VF including fatal acidosis induced by muscle contractions and induced respiratory arrest [90]. Over a century of electrocution, research has never demonstrated a single death from electrically induced acidosis from muscle contractions. The acidosis *from respiratory arrest* theory was popular in the later 1800s but Jones questioned this based on witnessed human accidents in 1895 [91]. Oliver and Bolam then did animal experiments which showed that electrocution was due to an immediate cardiac arrest, in their 1898 paper [92]. Fatal acidosis *from respiratory arrest* was demonstrated by Cunningham in the 1890s in dogs but only with 10 min of continuous currents just below those required for VF [93]. This is irrelevant to CEWs since they do not cause respiratory arrest [94–98].

A more curious hypothesis was that the muscle contractions could cause a delayed death from rhabdomyolysis and subsequent acute kidney failure. This has been refuted with numerous clinical studies showing no meaningful increases in myoglobin or creatine kinase [99].

Diagnosing a CEW Electrocution

Objective criteria can be given for an electrocution diagnosis in a CEW incident as shown in Table 6.

Asystole (flatline) and PEA (pulseless electrical activity) are not inducible with electrical stimulation [100]. Asystole is rarely confused by EMS personnel—and almost never if multiple leads are used [101]. Electrically induced VF does not deteriorate to asystole in < 20 min [102–104] and the

Table 6 Diagnosis of electrocution by CEW. Each criterion must be satisfied

	Item	Notes
1	Presenting rhythm is VF [100].	Asystole and PEA are not inducible [100].
2	Dart-to-epicardial distance is ≤ 4 mm [76].	The critical DTH is 5.8 ± 2.1 mm in swine [76].
3	No documented pulse after CEW application.	When a pulse is detected, this has a 95% accuracy [110, 111].
4	Cessation of normal breathing within 60 s of CEW application [112, 113].	
5	Cessation of agonal breathing within 6 min of CEW application [113, 114].	Commonly referred to as "dying gasps" and not confused with normal breathing.
6	If defibrillation (up to 3 shocks) is attempted within 10 min (or 14 min with CPR) it is successful [109].	Electrically induced VF is defibrillated with a 90% success rate at 10 min with any chest compressions [109].

Table 7 Reported VF cases from CEW use

Age/race	DTH (mm)	Breathing (min)	failure of prompt defibrillation	Cardiac pathology
25 B	> 20	UNK	Y	Hypertrophy, fibrosis
48 C	No penetration	UNK	Y	Long QT
17 B	Right side	4	Y	Hypertrophic cardiomyopathy
17 B	50	4	Y	None on autopsy
16 B	55	8	Y	Arrhythmogenic right ventricular cardiomyopathy

median time in swine is 34 min [105]. The delay is longer with chest compressions [106].

The best evidence suggests that electrocution in a human would require that the tip of the probe be within ≈ 4 mm of the epicardium (outer part of the heart). This is not an issue with the drive stun as no probe penetrates the skin and gets sufficiently close to the heart. A probe in the sternum is considered too far away as the sternum is an insulator in adults [107, 108].

With any chest compressions, defibrillation has a ≥ 90% success rate up to 10 min of electrically induced VF—with 3 or fewer shocks [109]. Hence, the failure of prompt defibrillation exculpates an electrical cause for VF.

After a cardiac arrest, normal breathing ceases in 12–60 s [112, 113]. However, some subjects will also have "agonal" breathing (dying gasps) for a maximum total of 6 min [114].

Electrocution Anecdotes

There exist 12 published case reports suggesting electrocution by a CEW [115–120]. Case reports generally provide extremely weak evidence of causality because they are particularly prone to bias and are incomplete, uncontrolled, retrospective, and lack operational criteria for identifying when an adverse event has actually occurred [121, 122]. This is especially true regarding the CEW since the vast majority were generated in litigation [123]. A total of 9 of these 12 reports were from the expert witnessing activities of a single retired cardiologist [117, 118]. However, in the interest of a complete complication analysis, we will consider these case reports below.

In 49% of field uses a probe lands in the front chest [31]. Thus, we estimate that there have been about 1,911,000 field uses with a probe in the chest giving a potential incidence of 3.1 per million [95% CI 1.8–5.4] for any CEW discharge and 6.3 per million [95% CI 3.6–11.0] for a precordial probe application. Only 7 presented in VF. Another 2 can be eliminated as they included a case with missed probes and another case with a documented pulse afterwards. See Table 7 for the 5 remaining cases.

Electrocution can be diagnostically eliminated in the above cases by:

1. DTH ≥ 20 mm (vs. 3 mm): 5/5
2. Failure of prompt defibrillation [124]: 5/5
3. Breathing > 1 min [112, 113]: 3/5 (2 unknown)

All of the alleged VF case reports were analyzed by the Canadian Council of Science [125]. Their peer-reviewed report was produced by a deliberative panel that included numerous Canadian and US experts on electrical weapons and ARD, and was extensively peer-reviewed. This panel dismissed the controversial expert witness case series [117]. The Canadian Council report was very direct:

> The study by Zipes is particularly questionable since the author had a potential conflict of interest and used eight isolated and controversial cases as part of the analysis.

In summary, the risk of CEW-induced VF remains a theoretical concern with an extremely low probability. The risk appears to be confined to a very small or thin subject with a probe nearly touching the right ventricle. To date, no reported electrocution anecdote has withstood careful scrutiny [35, 99].

Conclusions

While reducing subject injury and death by about 2/3, CEW usage has a fatal complication rate of ≈ 6.7 per million, from uncontrolled falls and fume ignition. Penetrating eye injury appears to be the primary non-fatal major complication followed by rare non-fatal major burns and a single case of permanent brain injury from a fall. The non-fatal major complication rate is ≈ 6.4 per million.

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References

1. Wyant R (2014) Prevailing less lethal options for law enforcement. In: Risk Management of Less Lethal Options. CRC Press, Boca Raton, pp 65–100
2. Scherr C, de Carvalho AC, Belem LJ, Loyola LH, Guerra RL, Blanco F, Mangia C (2016) Cardiovascular effects of SPARK conducted electrical weapon in healthy subjects. Int J Cardiol 225:123–127. https://doi.org/10.1016/j.ijcard.2016.08.321
3. Nystrom PC (2012) The conducted electrical weapon: historical overview of the technology. In: Atlas of Conducted Electrical Weapon Wounds and Forensic Analysis. Springer, pp 1–23
4. Khaja A, Govindarajan G, McDaniel W, Flaker G (2010) Cardiac safety of conducted electrical devices in pigs and their effect on pacemaker function. Am J Emerg Med. https://doi.org/10.1016/j.ajem.2010.07.007
5. McDaniel WC (2008) Cardiac safety of the surface application of the Stinger s200. Biomed Sci Instrum 44:349–354
6. Esquivel AO, Dawe EJ, Sala-Mercado JA, Hammond RL, Bir CA (2007) The physiologic effects of a conducted electrical weapon in swine. Ann Emerg Med 50(5):576–583. https://doi.org/10.1016/j.annemergmed.2007.05.003
7. Vilke GM, Chan TC (2007) Less lethal technology: medical issues. Policing 30(3):341–357
8. White MD, Ready J (2007) The TASER as a less lethal force alternative: findings on use and effectiveness in a large metropolitan police agency. Police Q 10(2):170–191
9. Wolfe GM (2008) Electrical injury: are Tasers the new wave? University of, Toledo
10. Sweeney JD (2009) Theoretical comparisons of nerve and muscle activation by neuromuscular incapacitation devices. Conf Proc IEEE EMBC 31:3188–3190. https://doi.org/10.1109/IEMBS.2009.5334537
11. Criscione JC, Kroll MW (2014) Incapacitation recovery times from a conductive electrical weapon exposure. Forensic Sci Med Pathol 10(2):203–207. https://doi.org/10.1007/s12024-014-9551-x
12. Strote J, Verzemnieks E, Walsh M, Hutson HR (2010) Use of force by law enforcement: an evaluation of safety and injury. J Trauma 69(5):1288–1293. https://doi.org/10.1097/TA.0b013e3181c45302
13. Hall CA, Votova K, Heyd C, Walker M, MacDonald S, Eramian D, Vilke GM (2015) Restraint in police use of force events: examining sudden in custody death for prone and not-prone positions. J Forensic Legal Med 31:29–35
14. Vilke GM, Bozeman WP, Chan TC (2011) Emergency department evaluation after conducted energy weapon use: review of the literature for the clinician. J Emerg Med 40(5):598–604. https://doi.org/10.1016/j.jemermed.2010.10.019
15. Home_Office (2018) Police use of force statistics, England and Wales: April 2017 to March 2018.https://www.gov.uk/government/statistics/police-use-of-force-statistics-england-and-wales-april-2017-to-march-2018
16. An update on Taser use in Queensland (2012). Crime and Misconduct Commission: Research and Paper Series 9 (https://studylib.net/doc/8034073/research-and-issues%2D%2Dan-update-on-taser-use-in-queensland)
17. Kroll M (2019) North America brandishing and arcing data https://www.dropbox.com/s/83gst81hd87db84eg83/Kroll%20North%20America%20Brandishing%20and%20Arcing%20Data%202019.xlsx?dl=202010
18. Kaminski RJ, Edwards SM, Johnson JW (1998) The deterrent effects of oleoresin capsicum on assaults against police: testing the velcro-effect hypothesis. Police Q 1(2):1–20
19. Baldwin S, Hall C, Blaskovits B, Bennell C, Lawrence C, Semple T (2018) Excited delirium syndrome (ExDS): situational factors and risks to officer safety in non-fatal use of force encounters. Int J Law Psychiatry 60:26–34. https://doi.org/10.1016/j.ijlp.2018.06.011
20. Nakajima K, Vilke GM (2017) Use of force in the prehospital environment. In: Zeller SL, Nordstrom KD and Wilson MP (ed) The Diagnosis and Management of Agitation
21. MacDonald JM, Kaminski RJ, Smith MR (2009) The effect of less-lethal weapons on injuries in police use-of-force events. Am J Public Health 99(12):2268–2274
22. Taylor B, Woods DJ (2010) Injuries to officers and suspects in police use-of-force cases: a quasi-experimental evaluation. Police Q 13(3):260–289
23. Mesloh C, Wolf R, Henych M, Thompson F (2008) Less lethal weapons for law enforcement: a performance-based analysis. Law Enforcement Executive Forum 8(1):133–149
24. Mesloh C, Henych M, Wolf R (2008) Less lethal weapon effectiveness, use of force, and suspect & officer injuries: a five-year analysis. Report to the National Institute of Justice 224081:1–103
25. Mesloh C, Henych M, Hougland S, Thompson F (2005) TASER and less lethal weapons: an exploratory analysis of deployments and effectiveness. In: Law Enforcement Executive Forum. 5:67–79
26. Smith M, Kaminski R, Rojek J, Alpert G, Mathis J (2007) The impact of conducted energy devices and other types of force and resistance on officer and suspect injuries. Policing: An Int J Police Strateg Manag 30(3):423–446. https://doi.org/10.1108/13639510710778822
27. Butler C, Hall C (2008) Police/public interaction: arrests, use of force by police, and resulting injuries to subjects and officers—a description of risk in one major Canadian city. Law Enforcement Executive Forum 8(6):139–155
28. Jenkinson E, Neeson C, Bleetman A (2006) The relative risk of police use-of-force options: evaluating the potential for deployment of electronic weaponry. J Clin Forensic Med 13(5):229–241
29. Bozeman WP, Stopyra JP, Klinger DA, Martin BP, Graham DD, Johnson JC 3rd, Mahoney-Tesoriero K, Vail SJ (2018) Injuries associated with police use of force. J Trauma Acute Care Surg 84(3):466–472
30. Hickey ER, Hoffman PB (2003) To bite or not to bite: canine apprehensions in a large, suburban police department. J Crim Just 31(2):147–154
31. Bozeman WP, Hauda WE 2nd, Heck JJ, Graham DD Jr, Martin BP, Winslow JE (2009) Safety and injury profile of conducted electrical weapons used by law enforcement officers against criminal suspects. Ann Emerg Med 53(4):480–489. https://doi.org/10.1016/j.annemergmed.2008.11.021
32. Terrill W, Paoline EA (2011) Conducted energy devices (CEDs) and citizen injuries: the shocking empirical reality. Justice Q:1–30. https://doi.org/10.1080/07418825.2010.549834
33. Kaminski RJ, Engel RS, Rojek J, Smith MR, Alpert G (2015) A quantum of force: the consequences of counting routine conducted energy weapon punctures as injuries. Justice Q 32(4):598–625
34. Ba B, Grogger J (2018) The introduction of tasers and police use of force: evidence from the Chicago Police Department. National Bureau of Economic Research
35. Kroll MW, Lakkireddy DR, Stone JR, Luceri RM (2014) TASER electronic control devices and cardiac arrests: coincidental or causal? Circulation 129(1):93–100. https://doi.org/10.1161/CIRCULATIONAHA.113.004401
36. Karch SB (2016) The problem of police-related cardiac arrest. J Forensic Legal Med 41:36–41. https://doi.org/10.1016/j.jflm.2016.04.008
37. Hickman MJ, Piquero AR, Garner JH (2008) Toward a national estimate of police use of nonlethal force. Criminol Public Policy 7(4):563–604
38. Mumola C (2007) Arrest-related deaths in the United States, 2003-2005. Bureau of Justice Statistics Special Report (NCJ 219534): http://www.bjs.gov/index.cfm?ty=pbdetail&iid=379

39. Reuters (2018) THE REUTERS TRACKER: deaths involving tasers. reuterscom (https://www.reuters.com/investigates/special-report/usa-taser-tracker/)
40. Ferdik FV, Kaminski RJ, Cooney MD, Sevigny EL (2014) The influence of agency policies on conducted energy device use and police use of lethal force. Police Q 17:328–358. https://doi.org/10.1177/1098611114548098
41. Eastman AL, Metzger JC, Pepe PE, Benitez FL, Decker J, Rinnert KJ, Field CA, Friese RS (2008) Conductive electrical devices: a prospective, population-based study of the medical safety of law enforcement use. J Trauma 64(6):1567–1572
42. Ho J, Dawes D, Miner J, Kunz S, Nelson R, Sweeney J (2012) Conducted electrical weapon incapacitation during a goal-directed task as a function of probe spread. Forensic Sci Med Pathol 8(4): 358–366. https://doi.org/10.1007/s12024-012-9346-x
43. Kroll MW, Ritter MB, Kennedy EA, Siegal NK, Shinder R, Brave MA, Williams HE (2018) Eye injury from electrical weapon probes: mechanisms and treatment. Am J Emerg Med:epublished. https://doi.org/10.1016/j.ajem.2018.06.004
44. Kroll MW, Ritter MB, Kennedy EA, Silverman NK, Shinder R, Brave MA, Williams HE (2018) Eye injuries from electrical weapon probes: incidents, prevalence, and legal implications. J Forensic Legal Med 55:52–57. https://doi.org/10.1016/j.jflm.2018.02.013
45. Strote J, Walsh M, Angelidis M, Basta A, Hutson HR (2010) Conducted electrical weapon use by law enforcement: an evaluation of safety and injury. J Trauma 68(5):1239–1246. https://doi.org/10.1097/TA.0b013e3181b28b78
46. Gapsis BC, Hoang A, Nazari K, Morcos M (2017) Ocular manifestations of TASER-induced trauma. Trauma Case Rep 12:4–7. https://doi.org/10.1016/j.tcr.2017.10.001
47. Hajiaghamemar M, Seidi M, Ferguson JR, Caccese V (2015) Measurement of head impact due to standing fall in adults using anthropomorphic test dummies. Ann Biomed Eng:1–10
48. Hamel A, Llari M, Piercecchi-Marti M-D, Adalian P, Leonetti G, Thollon L (2013) Effects of fall conditions and biological variability on the mechanism of skull fractures caused by falls. Int J Legal Med 127(1):111–118
49. Kroll MW, Adamec J, Wetli CV, Williams HE (2016) Fatal traumatic brain injury with electrical weapon falls. J Forensic Legal Med 43:12–19. https://doi.org/10.1016/j.jflm.2016.07.001
50. Ho JD, Heegaard WG, Dawes DM, Natarajan S, Reardon RF, Miner JR (2009) Unexpected arrest-related deaths in america: 12 months of open source surveillance. West J Emerg Med 10(2):68–73
51. Drinker P, Yaglou C, Warren MF (1943) The threshold toxicity of gasoline vapor. J Ind Hyg Toxicol 25:225–232
52. Sandmeyer EE (1985) Aromatic hydrocarbons. In: Frank Arthur Patty GDC, Clayton FE, Battigelli MC (eds) Patty's industrial hygiene and toxicology, vol 2. John Wiley & Sons, Hoboken
53. Myers C, Wyant R, Burns T (2007) Taser safe, or flammable? Law Officer Magazine:38–41
54. Kroll M, Ritter M, Williams H (2017) Fatal and non-fatal burn injuries with electrical weapons and explosive fumes. J Forensic Legal Med 50:6–11
55. Zabetakis M (1965) Flammability characteristics of combustible gases and vapors. US Dept of the interior. Bureau of Mines, Washington DC
56. Underwriters_Laboratories (2003) UL 69: Electric fence controllers
57. Kroll MW, Perkins PE, Panescu D (2015) Electric fence standards comport with human data and AC limits. Conf Proc IEEE EMBC 37:1343–1348
58. International_Electrotechnical_Commission (2006) Household and similar electrical appliances – Safety – IEC 60335-2-76: Particular requirements for electric fence energizers
59. Nimunkar AJ, Webster JG (2009) Safety of pulsed electric devices. Physiol Meas 30(1):101–114
60. Walcott GP, Kroll MW, Ideker RE (2011) Ventricular fibrillation threshold of rapid short pulses. Conf Proc IEEE EMBC 33:255–258. https://doi.org/10.1109/IEMBS.2011.6090049
61. Panescu D, Nerheim M, Kroll M (2013) Electrical safety of conducted electrical weapons relative to requirements of relevant electrical standards. Conf Proc IEEE Eng Med Biol Soc 35:5342–5347
62. Panescu D, Nerheim M, Kroll MW, Brave M (2017) New conducted electrical weapons: electrical safety relative to relevant standards. Conf Proc IEEE EMBC 39:2185–2190
63. Rahko PS (2008) Evaluation of the skin-to-heart distance in the standing adult by two-dimensional echocardiography. J Am Soc Echocardiogr 21(6):761–764. https://doi.org/10.1016/j.echo.2007.10.027
64. Horowitz LN, Spear JF, Moore EN (1981) Relation of the endocardial and epicardial ventricular fibrillation thresholds of the right and left ventricle. Am J Cardiol 48(4):698–701
65. Spear J, Horowitz L, Moore E (1977) Relationship of endocardial and epicardial ventricular-fibrillation thresholds of right and left-ventricles. Am J Cardiol 39(2):274-274
66. Horowitz LN, Spear JF, Josephson ME, Kastor JA, Moore EN (1979) The effects of coronary artery disease on the ventricular fibrillation threshold in man. Circulation 60(4):792–797
67. Allison JS, Qin H, Dosdall DJ, Huang J, Newton JC, Allred JD, Smith WM, Ideker RE (2007) The transmural activation sequence in porcine and canine left ventricle is markedly different during long-duration ventricular fibrillation. J Cardiovasc Electrophysiol 18(12):1306–1312
68. Brave MA, Lakkireddy DR, Kroll MW (2016) Validity of the small swine model for human electrical safety risks. Conf Proc IEEE EMBC 38:2343–2348. https://doi.org/10.1109/EMBC.2016.7591200
69. Hamlin RL, Burton RR, Leverett SD, Burns JW (1975) Ventricular activation process in minipigs. J Electrocardiol 8(2): 113–116
70. Kano M, Toyoshi T, Iwasaki S, Kato M, Shimizu M, Ota T (2005) QT PRODACT: usability of miniature pigs in safety pharmacology studies: assessment for drug-induced QT interval prolongation. J Pharmacol Sci 99(5):501–511
71. Walcott GP, Kroll MW, Ideker RE (2015) Ventricular fibrillation: are swine a sensitive species? J Interv Card Electrophysiol 42(2): 83–89. https://doi.org/10.1007/s10840-014-9964-1
72. Valentino DJ, Walter RJ, Dennis AJ, Margeta B, Starr F, Nagy KK, Bokhari F, Wiley DE, Joseph KT, Roberts RR (2008) Taser X26 discharges in swine: ventricular rhythm capture is dependent on discharge vector. J Trauma 65(6):1478–1485 discussion 1485-1477
73. Geddes LA, Cabler P, Moore AG, Rosborough J, Tacker WA (1973) Threshold 60-Hz current required for ventricular fibrillation in subjects of various body weights. IEEE Trans Biomed Eng 20(6):465–468. https://doi.org/10.1109/TBME.1973.324221
74. Han J, Garciadejalon P, Moe GK (1964) Adrenergic effects on ventricular vulnerability. Circ Res 14:516–524
75. Papp JG, Szekeres L (1968) Analysis of the mechanism of adrenergic actions on ventricular vulnerability. Eur J Pharmacol 3(1): 15–26
76. Wu JY, Sun H, O'Rourke AP, Huebner SM, Rahko PS, Will JA, Webster JG (2008) Taser blunt probe dart-to-heart distance causing ventricular fibrillation in pigs. IEEE Trans Biomed Eng 55(12):2768–2771
77. Dawes DM, Ho JD, Moore JC, Miner JR (2013) An evaluation of two conducted electrical weapons and two probe designs using a swine comparative cardiac safety model. Forensic Sci Med Pathol 9(3):333–342. https://doi.org/10.1007/s12024-013-9422-x

78. Lakkireddy D, Wallick D, Verma A, Ryschon K, Kowalewski W, Wazni O, Butany J, Martin D, Tchou PJ (2008) Cardiac effects of electrical stun guns: does position of barbs contact make a difference? Pacing Clin Electrophysiol 31(4):398–408
79. Lakkireddy D, Wallick D, Ryschon K, Chung MK, Butany J, Martin D, Saliba W, Kowalewski W, Natale A, Tchou PJ (2006) Effects of cocaine intoxication on the threshold for stun gun induction of ventricular fibrillation. J Am Coll Cardiol 48(4):805–811. https://doi.org/10.1016/j.jacc.2006.03.055
80. Kroll MW, Lakkireddy D, Rahko PS, Panescu D (2011) Ventricular fibrillation risk estimation for conducted electrical weapons: critical convolutions. Conf Proc IEEE Eng Med Biol Soc 33:271–277. https://doi.org/10.1109/IEMBS.2011.6090053
81. Chilbert M (1998) Standards and rationale. In: Reilly J (ed) Applied bioelectricity: from electrical stimulation to electrical pathology. Springer, New York, pp 454–501
82. Sun H, Haemmerich D, Rahko PS, Webster JG (2010) Estimating the probability that the Taser directly causes human ventricular fibrillation. J Med Eng Technol 34(3):178–191. https://doi.org/10.3109/03091900903509149
83. Gardner AR, Hauda WE 2nd, Bozeman WP (2012) Conducted electrical weapon (TASER) use against minors: a shocking analysis. Pediatr Emerg Care 28(9):873–877. https://doi.org/10.1097/PEC.0b013e31826763d1
84. Panescu D, Kroll MK, Brave MA (2015) Cardiac fibrillation risks with TASER conducted electrical weapons. Conf Proc IEEE EMBC 37:323–329. https://doi.org/10.1109/EMBC.2015.7318365
85. Kroll MW, Lakkireddy D, Rahko PS, Panescu D (2011) Ventricular fibrillation risk estimation for conducted electrical weapons: critical convolutions. Conf Proc IEEE EMBC 33:271–277. https://doi.org/10.1109/IEMBS.2011.6090053
86. Stopyra JP, Winslow JE, Fitzgerald DM, Bozeman WP (2017) Intracardiac electrocardiographic assessment of precordial TASER shocks in human subjects: a pilot study. J Forensic Legal Med 52:70–74. https://doi.org/10.1016/j.jflm.2017.08.004
87. Dawes DM, Ho JD, Reardon RF, Miner JR (2010) Echocardiographic evaluation of TASER X26 probe deployment into the chests of human volunteers. Am J Emerg Med 28(1):49–55. https://doi.org/10.1016/j.ajem.2008.09.033
88. Ho JD, Dawes DM, Reardon RF, Strote SR, Kunz SN, Nelson RS, Lundin EJ, Orozco BS, Miner JR (2011) Human cardiovascular effects of a new generation conducted electrical weapon. Forensic Sci Int 204(1-3):50–57. https://doi.org/10.1016/j.forsciint.2010.05.003
89. Ideker RE, Dosdall DJ (2007) Can the direct cardiac effects of the electric pulses generated by the TASER X26 cause immediate or delayed sudden cardiac arrest in normal adults? Am J Forensic Med Pathol 28(3):195–201
90. Fish RM, Geddes LA (2001) Effects of stun guns and tasers. Lancet 358(9283):687–688
91. Jones HL (1895) The lethal effects of electrical currents. Br Med J 1(1783):468–470
92. Oliver T, Bolam RA (1898) Cause of death by electric shock. Br Med J 1(1933):132–135
93. Jex-Blake A (1913) Death by electric currents and lightning. Br Med J 1:425–603
94. Ho JD, Dawes DM, Chang RJ, Nelson RS, Miner JR (2014) Physiologic effects of a new-generation conducted electrical weapon on human volunteers. J Emerg Med 46(3):428–435. https://doi.org/10.1016/j.jemermed.2013.08.069
95. Dawes DM, Ho JD, Reardon RF, Sweeney JD, Miner JR (2010) The physiologic effects of multiple simultaneous electronic control device discharges. West J Emerg Med 11(1):49–56
96. Dawes DM, Ho JD, Reardon RF, Miner JR (2010) The cardiovascular, respiratory, and metabolic effects of a long duration electronic control device exposure in human volunteers. Forensic Sci Med Pathol 6(4):268–274. https://doi.org/10.1007/s12024-010-9166-9
97. Vilke GM, Sloane CM, Suffecool A, Kolkhorst FW, Neuman TS, Castillo EM, Chan TC (2009) Physiologic effects of the TASER after exercise. Acad Emerg Med 16(8):704–710
98. Vilke GM, Sloane CM, Bouton KD, Kolkhorst FW, Levine SD, Neuman TS, Castillo EM, Chan TC (2007) Physiological effects of a conducted electrical weapon on human subjects. Ann Emerg Med 50(5):569–575
99. Kunz SN, Calkins H, Adamec J, Kroll MW (2018) Cardiac and skeletal muscle effects of electrical weapons : a review of human and animal studies. Forensic Sci Med Pathol 14(3):358–366. https://doi.org/10.1007/s12024-018-9997-3
100. Zima E, Gergely M, Soos P, Geller LA, Nemes A, Acsady G, Merkely B (2006) The effect of induction method on defibrillation threshold and ventricular fibrillation cycle length. J Cardiovasc Electrophysiol 17(4):377–381. https://doi.org/10.1111/j.1540-8167.2006.00352.x
101. Cummins RO, Austin D Jr (1988) The frequency of 'occult' ventricular fibrillation masquerading as a flat line in prehospital cardiac arrest. Ann Emerg Med 17(8):813–817
102. Robertson PG, Huang J, Chen KA, Chen X, Dosdall DJ, Tabereaux PB, Smith WM, Ideker RE (2009) Increased cycle length during long-duration ventricular fibrillation is caused by decreased upstroke velocity as well as prolonged refractoriness. Heart Rhythm 6(3):378–384. https://doi.org/10.1016/j.hrthm.2008.12.016
103. Worley SJ, Swain JL, Colavita PG, Smith WM, Ideker RE (1985) Development of an endocardial-epicardial gradient of activation rate during electrically induced, sustained ventricular fibrillation in dogs. Am J Cardiol 55(6):813–820
104. Wiggers CJ (1930) Studies of ventricular fibrillation caused by electric shock: I. Am J Phys 92:223–239
105. Kroll MW, Walcott GP, Ideker RE, Graham MA, Calkins H, Lakkireddy D, Luceri RM, Panescu D (2012) The stability of electrically induced ventricular fibrillation. Conf Proc IEEE Eng Med Biol Soc 34:6377–6381. https://doi.org/10.1109/EMBC.2012.6347453
106. White RD, Goodman BW, Svoboda MA (2011) Neurologic recovery following prolonged out-of-hospital cardiac arrest with resuscitation guided by continuous capnography. Mayo Clin Proc 86(6):544–548. https://doi.org/10.4065/mcp.2011.0229
107. Panescu D, Kroll M, Iverson C, Brave M (2014) The sternum as an electrical shield. Conference proceedings : Annual International Conference of the IEEE Engineering in Medicine and Biology Society IEEE Engineering in Medicine and Biology Society Annual Conference 2014:4464–4470. https://doi.org/10.1109/EMBC.2014.6944615
108. Panescu D, Kroll MW, Brave M (2017) New conducted electrical weapons: thoracic cage shielding effects. Conf Proc IEEE EMBC 39:2191–2196
109. Kroll MW, Fish RM, Calkins H, Halperin H, Lakkireddy D, Panescu D (2012) Defibrillation success rates for electrically-induced fibrillation: hair of the dog. Conf Proc IEEE Eng Med Biol Soc 34:689–693. https://doi.org/10.1109/EMBC.2012.6346025
110. Bahr J, Klingler H, Panzer W, Rode H, Kettler D (1997) Skills of lay people in checking the carotid pulse. Resuscitation 35(1):23–26
111. Dick WF, Eberle B, Wisser G, Schneider T (2000) The carotid pulse check revisited: what if there is no pulse? Crit Care Med 28(11 Suppl):N183–N185
112. Haouzi P, Ahmadpour N, Bell HJ, Artman S, Banchs J, Samii S, Gonzalez M, Gleeson K (2010) Breathing patterns during cardiac arrest. J Appl Physiol 109(2):405–411. https://doi.org/10.1152/japplphysiol.00093.2010

113. Zuercher M, Ewy GA, Otto CW, Hilwig RW, Bobrow BJ, Clark L, Chikani V, Sanders AB, Berg RA, Kern KB (2010) Gasping in response to basic resuscitation efforts: observation in a swine model of cardiac arrest. Crit Care Res Pract 10(36):1–7. https://doi.org/10.1155/2010/351638
114. Clark JJ, Larsen MP, Culley LL, Graves JR, Eisenberg MS (1992) Incidence of agonal respirations in sudden cardiac arrest. Ann Emerg Med 21(12):1464–1467
115. Kim PJ, Franklin WH (2005) Ventricular fibrillation after stun-gun discharge. N Engl J Med 353(9):958–959
116. Schwarz ES, Barra M, Liao MM (2009) Successful resuscitation of a patient in asystole after a TASER injury using a hypothermia protocol. Am J Emerg Med 27(4):515 e511–515 e512
117. Zipes DP (2012) Sudden cardiac arrest and death following application of shocks from a TASER electronic control device. Circulation 125(20):2417–2422. https://doi.org/10.1161/CIRCULATIONAHA.112.097584
118. Zipes D (2009) Are you Tasing me? Tasers can cause fatal [ventricular Tachy]arrhythmias: HRS debate. Accessed Jan 15 2010
119. Naunheim RS, Treaster M, Aubin C (2010) Ventricular fibrillation in a man shot with a taser. Emerg Med J 27(8):645–646. https://doi.org/10.1136/emj.2009.088468
120. Swerdlow CD, Fishbein MC, Chaman L, Lakkireddy DR, Tchou P (2009) Presenting rhythm in sudden deaths temporally proximate to discharge of TASER conducted electrical weapons. Acad Emerg Med 16(8):726–739
121. Karch SB (2007) Peer review and the process of publishing of adverse drug event reports. J Forensic Legal Med 14(2):79–84
122. Ho PM, Peterson PN, Masoudi FA (2008) Evaluating the evidence: is there a rigid hierarchy? Circulation 118(16):1675–1684. https://doi.org/10.1161/CIRCULATIONAHA.107.721357
123. Zipes DP (2013) Acknowledgement of Atty. John Burton for sudden cardiac arrest and death following application of shocks from a TASER electronic control device. Circulation 127 http://circ.ahajournals.org/content/127/23/e839:e839. https://doi.org/10.1161/CIR.0b013e31829bd44a
124. Kroll MW, Fish RM, Calkins H, Halperin H, Lakkireddy D, Panescu D (2012) Defibrillation success rates for electrically-induced fibrillation: hair of the dog. Conf Proc IEEE EMBC 34: 689–693. https://doi.org/10.1109/EMBC.2012.6346025
125. Goudge S (2013) The health effects of conducted energy weapons: the expert panel on the medical and physiological impacts of conducted energy weapons. Council of Canadian Academies:http://www.scienceadvice.ca/en/assessments/completed/cew.aspx