

Brief Reports

PHYSIOLOGIC EFFECTS OF A NEW-GENERATION CONDUCTED ELECTRICAL WEAPON ON HUMAN VOLUNTEERS

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Abstract—Background: Conducted electrical weapons (CEWs) are used by law enforcement to restrain or repel potentially violent persons. The TASER X2 CEW is a next-generation device with new technology, including new electrical waveform and output specifications. It has not previously been studied in humans. **Objective:** The objective of this study was to evaluate the human physiologic effect of a new-generation CEW. **Methods:** This was a prospective, observational human study. Volunteers received a 10-s exposure via deployed probes from an X2 CEW in the abdomen and upper thigh. Measured data included vital signs; 12-lead electrocardiograms; and blood serum biomarkers before, immediately after, and 24 h post exposure. Biomarkers measured included pH, lactate, potassium, creatine kinase (CK), and troponin-I. Real-time spirometry and echocardiography were performed before, during, and after the exposure. **Results:** Ten volunteers completed the study. There were no important changes in vital signs or potassium. Median increase in lactate as a consequence of the exposure was 1.2 mg/dL (range 0.6–2.8 mg/dL). Median change in pH was –0.031 (range –0.011 to –0.067). No subject had a positive troponin. Median change in CK at 24 h was 313 ng/mL (range –40 to 3418 ng/mL). There was no evidence of respi-

ratory impairment. Baseline median minute ventilation was 14.2 L/min, increased to 21.6 L/min intra-exposure ($p = 0.05$), and remained elevated at 21.6 L/min post exposure ($p = 0.01$). **Conclusions:** There was no evidence of dangerous physiology found in the measured parameters. The physiologic effects of the X2 CEW are similar to older-generation CEWs. We encourage further study to validate these results. © 2014 Elsevier Inc.

Keywords—TASER; electronic control device; conducted electrical weapon; human physiology

INTRODUCTION

Conducted electrical weapons (CEWs) are used by law-enforcement officers (LEOs) as intermediate weapons, defined as items that generally can induce subject compliance due to pain or incapacitation and are a level above empty-hand control techniques but less than deadly force. They have filled a gap left by other law-enforcement devices, tactics, or tools and have been shown to reduce LEO and suspect injuries (1–3). CEWs deliver electrical charge from a capacitor system in discrete pulses at fast rates (19 pulses per second in most models) leading to the depolarization of peripheral motor neurons within a “zone of capture.” This results in subsequent involuntary

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subtetanic muscle contraction. The devices also depolarize afferent sensory neurons leading to pain.

The TASER X26 CEW (Figure 1) is currently the most prevalent CEW in use in the world and has been in service since 2003. It is considered to be older-generation technology and is based on electrical waveform characteristics developed more than a decade ago. Its operational limitations include the ability to fire a single cartridge only without reloading. This can present a distinct disadvantage during scenarios with unsuccessful current delivery (such as missing probe contact with the intended target), if the probe spread distance is too close to be effective, or there are multiple subjects to engage. There have been numerous human physiology studies performed using the older-technology X26 CEW (4–14). The older-technology CEWs are understood by experts to be safe and the newer-technology CEWs are proposed to be even safer. The TASER X2 CEW (Figure 2) represents new-generation CEW technology and has completely different waveform and output specifications that have significantly changed the electrical characteristics of this weapon when compared with previous CEWs. It also has the capability of firing two cartridges in a “semi-automatic” mode. This study is the first to examine comprehensive human physiologic effects of this newer-generation CEW.

METHODS

This was a prospective, observational study of human subjects. The Minneapolis Medical Research Foundation Institutional Review Board (Minneapolis, MN) approved this study. The study was conducted at the CEW manufacturer corporate headquarters in Scottsdale, AZ during a 2-day time period. The study volunteers were a convenience sample of LEOs or correctional officers partici-



Figure 1. Old generation TASER X26 CEW.



Figure 2. New generation TASER X2 CEW.

pating in a training exercise and receiving an X2 CEW exposure as part of their training. They were approached during their training course with the offer to be a part of this study. Declining to participate in this study did not absolve them from receiving CEW exposure during training.

The volunteers provided informed consent and completed a medical history questionnaire that was reviewed by a study physician. There were no specific exclusion criteria except known pregnancy and subjects had to be at full-duty status with their department and taking part in the training course. Each study volunteer was given a TASER X26 CEW as compensation for their participation.

Each volunteer had an i.v. placed by a certified paramedic before the testing. Baseline vital signs (blood pressure, heart rate, and pulse oximetry) were measured with an automated machine (Nonin 2120 Tabletop Monitor, Plymouth, MN) and baseline blood sampling from the i.v. occurred for the following values: creatine kinase (CK), potassium, pH, lactate, and troponin-I. The pH and lactate were immediately analyzed after withdrawing the blood sample using a Point-of-Care i-STAT analyzer and CG4 cartridges (Abbott Laboratories, East Windsor, NJ). The remaining blood was centrifuged and stored on site in ice, and transported at the end of each testing day to a local professional laboratory analysis site (Laboratory Corporation of America, Burlington, NC) for completion of the remaining tests. A commercial skin resistance analyzer (Omron Fat Loss Monitor HBF-306, Omron Healthcare, Inc., Bannockburn, IL) was used to determine body-fat percentage. All volunteers had been instructed to refrain from significant exertion for 24 h before and after their CEW exposure to avoid confusing their blood sample analyses.

The volunteers were fitted with face, neck, and groin protection and wore athletic shorts. Male volunteers wore no shirt and female volunteers wore a T-shirt or

sports bra, depending on their preference. ATASER Master Instructor deployed X2 probes into the volunteers from 10 feet (3.05 meters) with a modified X2 CEW that fired the probes, but did not discharge any electrical charge into the volunteers. The X2 cartridges used were factory standard. The probe deployments were made into frontal locations consistent with recommended target sites per the manufacturer. The superior probe deployment location was within the abdomen and the inferior probe deployment location was within the thigh.

After the initial probe deployment, each volunteer was laid supine for testing and a factory-standard X2 CEW field-deployable device was attached to the previously fired cartridge. Each volunteer was fitted with a neoprene mask and comprehensive, continuous respiratory data were collected using an Ultima CPX breath-by-breath gas exchange analyzer system (Medical Graphics, Inc., St Paul, MN). The system measured the oxygen and carbon dioxide concentrations, respiratory rate, and tidal volume on a breath-by-breath basis. Subjects had surface 12-lead electrocardiography (ECG) done immediately before the exposure (Welch Allyn Cardio-Perfect, Skaneateles Falls, NY). In addition, they had real-time echocardiography performed by a trained emergency physician using a Sonosite M-Turbo ultrasound machine with a 1- to 5-MHz phased-array transducer (Sonosite, Inc., Bothell, WA). A parasternal long-axis view, including the anterior leaflet of the mitral valve, was obtained to determine heart rate and regularity of rhythm. Ultrasonography was necessary to determine the rate and rhythm of cardiac activity because cardiac monitoring is insufficient to determine this due to CEW-created electrical artifact. The two-dimensional view of the heart was assessed in real time by the ultrasonographer before switching to M-mode for real-time measurement of the heart rate before, during, and after the CEW exposure. Echocardiography was able to be obtained in real time during CEW exposure because the conducted electrical current does not spread outside of the area of the CEW probe locations. Once baseline data were collected, each volunteer received a 10-s continuous exposure from the X2 CEW.

Vital signs and a 12-lead ECG were obtained immediately (within 1 min) after the exposure. Real-time echocardiography continued after the exposure until determination of the heart rate was obtained. Venous blood sampling occurred from the i.v. immediately after the exposure, and was repeated every 2 min until 10 min of time post exposure had elapsed. All venous blood samples were analyzed in the same fashion as the initial baseline samples. At the end of this time period, the i.v. was removed. All volunteers returned in 24 h for their final blood sample evaluation, which was accomplished by standard venipuncture.

The respiratory data were collected before, during, and for approximately 10 min after the exposure. Breeze Suite 6.2 software (Medical Graphics, St Paul, MN) was used to process the respiratory data. The software mean function was utilized to determine mean values for pre, during, and post exposure. ECGs were interpreted by a blinded emergency physician and were interpreted as either “normal” or “abnormal.” If abnormal, the physician was asked to list the specific concern or abnormality. All data was entered into an Excel spreadsheet (Microsoft Corp, Redmond, WA) and exported into STATA 10.0 (Stata Corp, College Station, TX) for statistical analysis.

RESULTS

Ten volunteers were enrolled in this study and none were excluded. Median age of the volunteers was 31.5 years (range 21–44 years), median body mass index (calculated as kg/m^2) was 29.4 (range 17.6–34.3), and 80% were male. There were no important changes in vital signs or measured potassium. Median increase in lactate during the exposure was 1.2 mg/dL (range 0.6–2.8 mg/dL). Median change in pH was -0.031 (range -0.011 to -0.067). No subject had a positive troponin immediately after the exposure or at 24 h after exposure. Median change in CK at 24 h was 313 ng/mL (range -40 to 3418 ng/mL). There was no evidence of impairment of breathing by spirometry. Baseline median minute ventilation was 14.2 L/min, increased to 21.6 L/min during the exposure ($p = 0.05$), and remained elevated at 21.6 L/min immediately post exposure ($p = 0.01$).

The baseline characteristics of the volunteers are presented in Table 1. The main results are shown in Table 2. The pH and lactate data are summarized graphically in Figures 3 and 4, respectively. Respiratory data are presented in Table 3. Of the ECGs, there were two subjects who had “normal” ECGs before the test and had “sinus tachycardia” interpreted immediately after their exposure, and there was one subject that had “possible right heart strain” interpreted on both the pre and post-exposure ECG. All other ECGs were interpreted as normal.

Table 1. Subject Baseline Data

	Median	Range	IQR
Age (years)	31.5	21–44	25–39
% Body fat	22.1	12.6–31.5	20.7–26.3
BMI	29.4	17.6–34.3	26.5–30.0
Heart rate (bpm)	89	76–99	87–91
Heart rate by echo (bpm)	86	71–105	85–87
Systolic blood pressure (mm Hg)	136	122–155	135–137
Diastolic blood pressure (mm Hg)	78	74–85	76–80
Creatine kinase (ng/mL)	84.5	40–811	63–210
Potassium (mmol/L)	3.65	3.5–4.1	3.6–3.9

BMI = body mass index (calculated as kg/m^2); IQR = interquartile range.

Table 2. Subject Post-CEW Exposure Data

	Median	Range	IQR
Cardiac echo during exposure (bpm)	120	107–136	115–125
Cardiac echo 10 min post exposure (bpm)	93	73–120	81–105
Heart rate post exposure (bpm)	99.5	73–113	87–110
Systolic BP post exposure (mm Hg)	135	116–166	133–143
Diastolic BP post exposure (mm Hg)	79	60–106	73–82
CK post exposure (ng/mL)	84.5	40–822	63–210
CK 24 h post exposure (ng/mL)	84	40–800	77–199
Potassium post exposure (mmol/L)	3.9	3.4–4.7	3.5–4.1
Potassium 24 h post exposure (mmol/L)	3.75	3.4–4.7	3.5–3.8

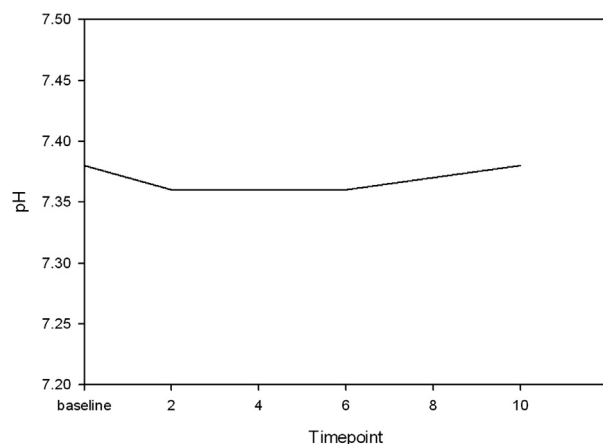
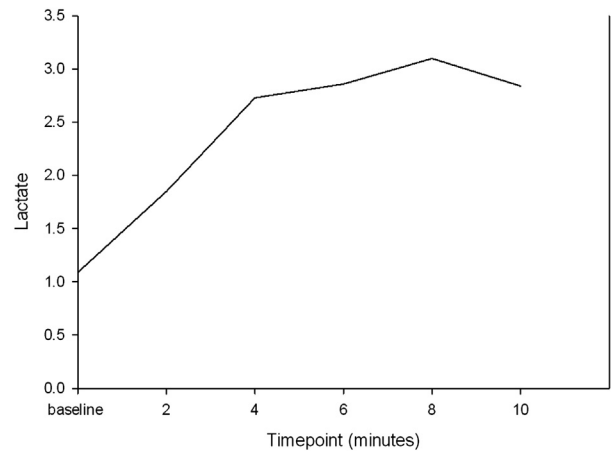
BP = blood pressure; CK = creatine kinase; IQR = interquartile range.

Unfortunately, there was variable compliance with the pre and post-exposure exercise/exertion restriction request. We contacted all subjects with CK values > 500 ng/mL. No subjects had clinical complaints of rhabdomyolysis (e.g., dark urine, fever, flank pain, unusual muscle pain or weakness). All subjects with CK values > 500 ng/mL admitted to disregarding the exercise restriction and engaged in strenuous muscular exertion (i.e., intentional workouts at a gym) within 24 h of attending the training course.

DISCUSSION

Cardiac

We did not find a demonstrably harmful cardiac effect in our study. Studies by several authors have shown no changes in surface ECG or serum troponin, a measure of heart muscle damage, after an exposure to a TASER X26 CEW, from 1 to 15 s, and with and without exertion

**Figure 3. Median pH over time.****Figure 4. Median lactate (mg/dL) over time.**

(4,6,8–10,14,15). In addition, human studies involving chest exposures with an X26 CEW have not demonstrated direct cardiac capture, even with prolonged or repetitive exposures, in rested and exhausted volunteers (7,12,16–19).

There has been a single report of a cardiac capture event in a human with an experimental CEW that was not released for field use (19). In that case, exposure was to the chest immediately adjacent to the sternum and the dart tip to heart distance was 16.7 mm (with a slight pectus excavatum of the chest). The subject had a real-time echocardiographically viewed capture rate of 240 beats/min but had no clinical complaint, had a normal post-exposure ECG, and had a negative troponin at 24 h.

Ideker and Dosdall estimated that the current from a TASER X26 CEW was 2.63 standard deviations less than the current needed to stimulate an ectopic beat, and that only 0.4% of individuals would have a paced beat from a TASER X26 pulse at the most sensitive position on the chest (20). We did not demonstrate any evidence of cardiac capture in this study, although our targeting was below the chest and was consistent with the preferred target zone as recommended by the CEW manufacturer. This target zone is low center mass and is consistent with the recommended target zones for other projectile intermediate weapons, such as fired beanbag or baton rounds. It is expected that shots within this target zone would have a near zero chance of inducing a cardiac effect.

Respiratory

Our study showed an increase in minute ventilation during the X2 CEW exposure. This was achieved primarily through a significant increase in respiratory rate. We believe that this phenomenon is likely due to the breathing pattern exhibited by people under acute pain or stress

Table 3. Subject Respiratory Data

	Pre Exposure		During Exposure		Post Exposure	
	Median	Range	Median	Range	Median	Range
Respiratory rate (breaths/min)	14.5	6–24	29	8–58	20	8–22
Tidal volume (L)	0.96	0.74–1.68	0.68	0.44–1.71	1.25	1.21–1.66
Minute ventilation (L/min)	14.2	10.6–19.8	21.6	13.5–40.3	21.6	13.9–29.4

situations. This finding is also consistent with the results from prior X26 CEW respiratory studies. In those studies, no clinically important effects on respiration were found with single device discharges, including durations up to 30 s continuously (4,6,18,21). There was no evidence of induced apnea in our data.

Venous pH

The pH is important in the discussion of CEW effect on physiology. CEWs are often used on persons in acidotic states. This acidotic state might be due to stimulant intoxication, physical resistance to LEOs, excited delirium syndrome, or a combination of all three. The discussion of acid–base balance is important because there is literature to support that when persons die suddenly and unexpectedly while in custody, they are often profoundly acidotic (22). Because CEWs are often used to control persons in these situations, it is important to know whether or not new technology CEWs could significantly contribute to this condition.

In a study by Vilke et al. using 5-s exposures from the TASER X26, the pH dropped from a mean baseline of 7.45 to 7.42 at 1 min and returned to 7.43 at 10 min (23). Lactate rose from a baseline of 1.4 mg/dL to 2.8 mg/dL at 1 min and 2.4 mg/dL at 10 min. A study by Ho et al., examined the effect of a 15-s TASER X26 discharge on already “exhausted” and acidotic adults, and found that the discharge did not significantly affect pH or lactate. Median pH after the exertion regimen but before the exposure was 7.23. After the exposure, the median was 7.22. Median lactate after the exertion regimen was 8.39 mg/dL, rising to 9.85 mg/dL after the exposure (24). In a follow-up study by Ho et al., a 15-s TASER X26 exposure was compared with an exertion regimen, and then to an exertion regimen followed by a 15-s exposure, and an exertion regimen followed by an additional 1 min of exertion (11). Exertion alone in this study produced profound pH drops at 2 min post-exertion. The study found no statistical difference between the TASER exposure and the additional brief exertion in the groups that had the initial exertion regimen. In another study with 10-s exposures, the pH dropped from 7.4 to 7.35 at 4 min, and the lactate rose from 1.3 mg/dL to 4.57 mg/dL at 6 min (21). In a study of 30-s durations, the pH drop-

ped from 7.36 to 7.27, with lactate rising from 1.46 mg/dL to 5.63 mg/dL (18). In a use of force comparison study, the median pH changed from 7.36 to 7.01 within 2 min after a 45-s heavy-bag resistance drill (punch and kick at maximal effort) (25). A 10-s TASER X26 exposure in comparison resulted in a median pH drop that was much less significant, from 7.37 to 7.29. This comparative study found that other arrest-related scenarios (fighting and fleeing) and typical uses of force are likely to produce more profound deleterious metabolic effects in a human than a CEW. The pH results in our current study with 10-s CEW exposures yielded results that were similar to this prior pH work described.

Electrolytes

Earlier CEW human studies have not demonstrated clinically important effects on electrolytes such as potassium (4,6). Our current study results are consistent with these findings for older-generation CEW technology. This is important to the discussion about sudden custodial deaths in which a CEW has been used temporally proximate to that death, often after a significant exertional struggle with LEOs has occurred. It has been theorized that a mechanism of acute intracellular potassium release under circumstances of extreme exertion followed by acute hypokalemia during recovery can pose a risk of sudden cardiac dysrhythmia due to sudden shifts in plasma potassium (26–28). Our study does not support a CEW contributing to this theory.

CK

Because CEWs are designed to stimulate skeletal muscle tissue, there is interest in knowing if they can induce clinically significant rhabdomyolysis. Rhabdomyolysis is clinically measured by CK and is important because massive rises in CK can lead acutely to hyperkalemia and renal failure (29).

In the seminal human CEW work by Ho et al., the baseline median CK was 185.1 U/L (range of 71–479 U/L). Median CK at 24 h after a 5-s X26 exposure was 242.3 U/L (range 52–909 U/L) (4). In a study by Dawes et al. examining the effects of two to three simultaneous 5-s discharges, the CK rises were higher, with a mean

CK at 24 h of 508 U/L for two simultaneous discharges and 1016 U/L for three simultaneous discharges (17). In a study by Dawes et al. with 30-s durations, median CK at baseline was 140 U/L, rising to only 187 U/L at 24 h (18). A meta-analysis by Dawes et al. showed a correlation between number of contact points (devices or circuits) and rise in CK, but no such relationship for duration (13). Our study on the newer-generation CEW indicates that the expected effect with regard to CK is similar to what has been found with previous technology.

Overall

Our study demonstrated that the physiologic effects of the new-generation TASER X2 are similar to the effects of previous-generation devices. Familiarity with effects from CEW exposures is important for the clinician. Laboratory values, vital signs, or clinical findings outside of the expected range should prompt the clinician to look for causes other than the CEW (such as intoxication, metabolic abnormality, etc.) The X2 CEW shows a reasonable safety profile with the duration of exposure tested. This is especially true when considering the context in which a CEW is used in society. The risk-to-benefit ratio balances society's need for controlling violent individuals from further harmful behavior with using a reasonable amount of force to do so. Although nothing can guarantee a zero-risk potential when violent behavior occurs and is met with use of reasonable force, the X2 CEW appears to have an acceptable physiologic safety profile if used per the manufacturer's recommendations. This assessment is supported by epidemiologic literature that indicates a decrease in injuries to LEOs and suspects and a low suspect injury rate with field use (30,31).

Limitations

Our study is limited by the relatively small number of subjects studied. The number studied was limited by the amount of time that it took to complete the entire evaluation of each volunteer. We believe, however, that our findings in these volunteers mimic the findings of earlier CEW human research.

Our study population might also be somewhat limiting because they were relatively healthy persons and not under the influence of illicit drugs or in the throes of a mental illness crisis, as many persons are that interact with LEOs and subsequently require a CEW application for behavior control. However, it was our goal to determine the basic, comprehensive effect of an X2 CEW on human physiology and we believe we accomplished that.

We acknowledge that we also had some noncompliance in our volunteers with the "no exertion/no exercise" instruction during the post-exposure period before their

24-h evaluation. We believe, however, that this would have led to artificially worse results in biomarkers such as CK or pH. If anything, this would cause us to be overly conservative in stating our conclusions.

CONCLUSIONS

In our study, there was no evidence of dangerous physiology found with any of our measured parameters. We conclude that the human physiologic effects of the X2 CEW are similar to previously studied older-generation CEWs. We recommend further study of emerging CEW technology to validate these results.

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ARTICLE SUMMARY

1. Why is this topic important?

Human physiology effects have been studied for older generation CEW technology. As older generation CEWs are replaced with newer CEW technology, it is important for medical professionals to know whether the new generation CEWs with different circuit specifications produce human physiologic effects that are different.

2. What does this study attempt to show?

This study is the first to examine the human physiologic effects of new generation CEWs with newer technology.

3. What are the key findings?

A 10-second frontal exposure with a new generation CEW in a manufacturer-recommended target zone did not demonstrate measurable harmful physiologic changes in human subjects. This is consistent with results from prior studies of older technology CEWs.

4. How is patient care impacted?

The findings from this study should guide clinicians caring for patients after a CEW exposure. The study results support the recommendations in prior literature that provides guidelines for post-CEW exposure evaluations and treatment. (Vilke GM, Bozeman WP and TC Chan. Emergency department evaluation after conducted energy weapon use: review of the literature for the clinician. J Emerg Med 2011;40:598-604.)