



A comparative brief on conducted electrical weapon safety

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Summary The variety and high number of published research articles on conducted electrical weapons (CEW) provides a detailed, yet in some parts inconclusive overview of medical aspects of CEW. Due to different research approaches and the use of dissimilar test subjects, an assessment of possible health risks of CEW is limited. The present work provides a brief on CEW safety based on currently available animal, computer and human research data. Using the medical database PubMed, articles published on this topic are critically evaluated and compared with each other. Special focuses are the differences and similarities of human and animal research as well as computer simulation programs. The authors explain why some studies are more reliable than others and give their expert opinion on the safety of CEW. The body of data that have been reviewed provides reasonable support for the safety of CEW.

Keywords Forensic medicine · Conducted electrical weapon · TASER · Ventricular fibrillation · Electricity

Eine vergleichende Sicherheitsanalyse von Elektroschockdistanzwaffen

Zusammenfassung Die Vielfalt und hohe Anzahl der veröffentlichten Forschungsergebnisse zum Thema der Elektroschockdistanzwaffen („conducted electrical weapons“, CEW) liefert einen detaillierten, aber nicht immer eindeutigen Überblick über medizini-

sche Aspekte dieser Geräte. Aufgrund unterschiedlicher Forschungsansätze und der Verwendung andersartiger Versuchsobjekte ist eine allgemeingültige und v. a. auch auf spezielle Einsatzszenarien übertragbare Einschätzung potenzieller Gesundheitsrisiken von CEW nur begrenzt möglich. Die vorliegende Arbeit gibt einen Überblick über die CEW-Sicherheit auf der Grundlage von derzeit verfügbaren Tier-, Computer- und humanen Forschungsdaten. Unter Nutzung der medizinischen Datenbank PubMed werden zu diesem Thema publizierte Artikel kritisch bewertet und miteinander verglichen. Besondere Schwerpunkte sind die Unterschiede und Gemeinsamkeiten von Human- und Tierforschung sowie von Computersimulationsprogrammen. Die Autoren erklären, warum ihrer Meinung nach manche Studien zuverlässiger sind als andere und geben eine Einschätzung zur Sicherheit von CEW ab. Die untersuchten Daten lassen die Sicherheit von CEW vertretbar erscheinen.

Schlüsselwörter Rechtsmedizin · Elektroschockdistanzwaffen · TASER · Kammerflimmern · Elektrizität

Introduction

On the basis of current political events throughout the world and the increasingly complex requirements for police officers to prevent and control criminal activities, conducted electrical weapons (CEW) have been introduced to police forces worldwide. With an increase in deployment, an increase in arrest-related fatalities has been observed [1]. It is natural that every time a subject experiences an arrest-related death in the setting of use of a CEW, the question as to whether the CEW caused or contributed to the death ensues. These cases are taken by the scientific community as an occasion to discuss potential health risks of this new technology. In the course of time, the debate

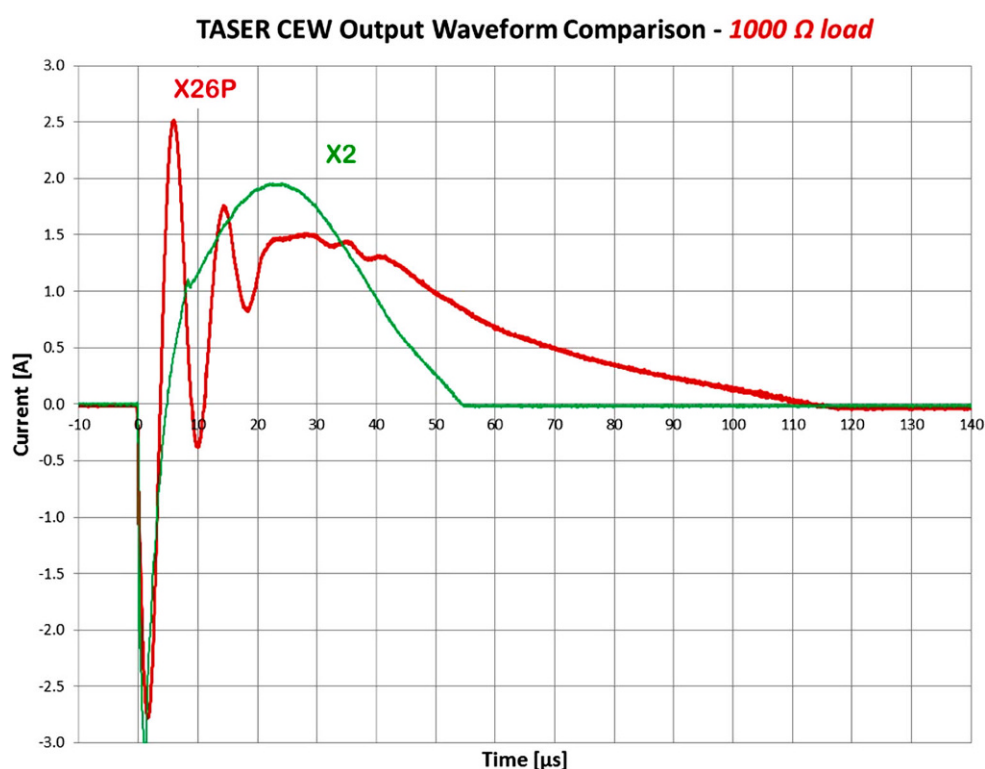
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Fig. 1 a TASER X26P, b TASER X2. (Images reproduced with permission from Axon Enterprise, Inc., Scottsdale, USA)

Fig. 2 Electrical wave-forms of a TASER X2 and X26P as a function of the input resistance at 1000Ω (Image reproduced with permission from Axon Enterprise, Inc., Scottsdale, USA)



has been driven by political, economic, medical and scientific interests, and in some aspects lost its original intention, which is to ensure the safety of these devices.

At present, CEW are mainly manufactured and distributed by AXON Enterprise, Inc. Similar models from other companies such as Defenders Network Inc., Stinger Systems or PHAZZER are not widely used and only very few research data exist. Commonly used CEW, such as the TASER X26P and the TASER X2 (Axon Enterprises, Inc., Scottsdale, USA, Fig. 1), are gun-like polymer plastic weapons with attachable cartridges, in which the ammunition is located in the form of two small barbed arrow electrodes. When

a person is hit, high-frequency current pulses of high voltage with simultaneously low current intensity (Table 1) are transferred via the metal probes into the body (Fig. 2). A cutaneous and muscular pain reaction is triggered in the body, followed by a locally limited or complete tetanic muscle contraction, depending on the hit localization and the distance of the electrodes [2]. This causes an involuntarily muscular spasm and thus makes the affected person incapacitated for the duration of the current application [3]. After removal of the dart electrodes, small superficial wounds remain, surrounded by reddening of the skin (Fig. 3).

Table 1 Electrical output parameters of TASER X26P and X2 in a typical load

Parameter	X26P	X2
Peak output current (A)	2.90	3.50
Peak voltage (kV)	1.75	1.40
Energy delivered (J/pulse)	0.10	0.09
Power (W)	1.75	1.70
Absolut charge in main phase (μC)	99.00	79.00
Impulse duration (μs)	126.00	56.00
Pulse rate (pulse/s)	18.45	19.15
Total delivery duration (s)	5.00	5.00

The purpose of this article is to give a short overview on current literature concerning the safety of these devices. Special focuses are the differences and similarities of human and animal research as well as computer simulation programs. The authors explain, from their point of view, why some studies are more reliable than others and give their conclusion on the safety of CEW. A particular focus of this article is to provide information on CEW, which is of value not only to forensic pathologists but also to emergency and general physicians.

Literature review

In order to find publications describing pathophysiological effects of CEW, a systematic online search of the PubMed database was performed, with the latest update done on November 6th, 2017. The following search terms were used: “Conducted Electrical Weapon”, “CEW”, “TASER”, “Electroshock Weapon”, “Electrical Weapon” and “Stun Gun”. Further publications were collected through a manual search of reference lists in retrieved articles. Papers published in languages other than English, German, Icelandic or Swedish were not reviewed. Publications that were on a different topic, based on title and abstract, were excluded. Out of these remaining papers we chose experimental (computer, animal and human) and overview articles as well as case studies.

The literature review on CEW with help of the search tool PubMed produced 534 matches, of which 286 publications fulfilled our requirements. 37% of the retrieved articles were experiment based, of which 27 papers presented computer simulations, 35 animal and 39 human research data. 6 other experiments examined comparison measurements with cardiac biomonitoring [4], the ignitability of petrol vapours [5] or experiments on outdated CEW, which are no longer distributed [6] and thus were not used in this study. 179 non-experimental articles included mostly review and opinion articles (68%) as well as case studies (24%).

The earliest work was published by Koscove in 1985 [7], in which he reviews ballistic and electrical considerations of CEW. The latest article on CEW has been written by Stopyra et al. [8], discussing intra-

shock electrocardiographic effects of an intentional transcardiac CEW discharge.

An analysis of German scientific medical literature has shown that there are an additional 16 published articles in the German language on the matter of CEW, among others one letter to editor [9], case reports [10, 11], one human study [12], as well as review and overview articles [13–16].

Discussion

The available research data on CEW have reached a level that is almost incomprehensible for someone who is not specialized in this area. Multiple research groups have developed complex computer simulation programs and conducted extensive experimental studies on animals and humans. However, in order to fully understand these studies, it is essential to understand the details of the experimental design of each of these studies. All scientific experiments (human and animal research as well as computer simulation models) are defined by their individual settings and, as such, cannot always replicate the multiple confounders of real life.

When looking at the scientific literature on this subject, a large number of current medical publications conclude that the health risk of CEW is very low in humans [12, 17–29]. Several animal studies on pigs [30–33] and dogs [34] as well as computer simulation models [35–39] and case studies [10, 11, 40] also support this safety assumption. On the other hand, there are research groups which found different effects [41–47]. Since these conclusions are primarily based on animal studies, the transferability to human data is questionable (see section below).

The reason for these sometimes divergent results concerning CEW lies primarily in different research approaches and the use of dissimilar experimental subjects. In order to gain an objective overview on the actual effects of CEW and thus to be able to fully assess possible health risks, the influence of CEW on physiological processes in the human body have to be investigated.

In the past, possible respiratory effects of CEW have been discussed [48–50]. VanMeenen et al. [48] detected a decrease in tidal volume and Vilke et al. [49, 50] found an increase in minute ventilation during/initially after the exposure. The problem with such a short 5-second exposure is that this time interval doesn't fully represent a breathing cycle. Furthermore, such interferences with respiratory capability could not be confirmed in human studies with long-term exposures of 15 and 30s [21, 22, 51]. Even a direct CEW exposure over the phrenic nerves did not have an effect on respiration [52].

In this context, a potential interference of CEW with the acid–base balance of the human body should be mentioned. Experimental animal [53–56] as well as human studies [21–23, 57–59] have detected statis-



Fig. 3 Dart penetration wound 5 min after CEW application (source: image taken during own human research project)

tically significantly lowered pH and elevated lactate levels with a CEW exposure, but without any clinically significant metabolic changes and full recovery after several hours.

However, the still most widely scrutinized and discussed pathophysiological effects of CEW are cardiac [13, 29, 35, 60], neuroendocrine [18, 22] and muscular [24] aspects, as well as possible interactions with the central nervous system [25] during and immediately after an exposure.

In order to be able to evaluate these potential pathophysiological changes in the human body, the influence of electrical current has to be defined.

Electrical thresholds of CEW

It is a well-known medical fact that the heart can be influenced by externally as well as internally applied current [61]. In the context of the use of CEW, the main question is whether or to what extent the transmitted current can electrically stimulate the heart. In general, the current effect on the human body depends on several factors, such as the exact electrode position, the organic resistance, the applied voltage, the exposure time and the current intensity actually reaching each organ [62]. Depending on these variables, different threshold values can be assumed for a potentially fatal contact with a particular current source. Several international research groups have analysed various application scenarios for different kinds of electrical current and defined individual thresholds. As yet, no recognized threshold data concerning CEW exist, the safety requirements of the International Electrotechnical Commission (IEC) are one possibility to consider when evaluating potential health risks of CEW. The IEC have determined thresholds for electrical fences [43, 63], medical devices [64] and for general electrical effects on humans and animals [65, 66]. The current pulse transmitted during a TASER application clearly lies within these given

standards and below the respective thresholds [67, 68]. Based on the research by the IEC, it can be stated that a pathophysiological effect of the current waveform to the heart or other internal organs is unlikely, assuming that the CEW has properly been applied. In this context, according to the company Axon Int., a proper application is considered a shot that avoids sensitive areas of the body such as the head, eyes, throat, directly above the heart or known pre-existing injury areas.

Animal research considering the cardiac effects of CEW

The validity in and foremost transferability of animal studies to humans are limited. A direct transferability of the results from animal experiments to humans has repeatedly been questioned in the scientific literature [69–72]. The main reasons for this are essential physiological and anatomical differences between an adult human being and the tested animals [37, 73]. Especially swine have a different anatomic heart structure and electrophysiology. Due to longer QT time intervals, shorter repolarization times and intramural Purkinje fibres, the pig's heart is significantly more sensitive than that of humans [74–80].

Individual animal studies claimed a direct effect of the TASER devices on the heart. Electrically induced ventricular fibrillation is the main risk factor found in these experiments [41–47]. However, this assumption has not yet been confirmed, neither by comparative human studies [12, 20, 21, 26, 27, 29, 81] nor in the case of statistical evaluations of CEW field usage [40, 82–85].

Taking into account the weight of the tested animals, it can be stated that the swine studies as a whole demonstrate that the theoretical risk of electrocution by CEW is confined to very small humans. Walcott et al. [86] have shown that swine are three times as sensitive to electrical current as humans. The largest swine that was used for these studies and which was successfully electrocuted was reported by Valentino et al. [43]. It had a weight of 36 kg. Using a body mass comparison to swine, the Valentino pig is equivalent to a 21 kg (46 lb) human. Thus, a potential cardiovascular risk in pigs with a dart-to-heart distance of <6 mm [79, 80] would correspond to a theoretically assumed human equivalence distance of <3 mm [67, 86, 87]. Because of the human anatomy, such a constellation is very unlikely in the case of a healthy adult. However, it should be mentioned that a correspondingly low dart-to-heart distance is possible in children with a cachectic body habitus or with a direct hit over the heart. In such cases, cardiac capture cannot be excluded.

Other animal research groups such as Nanthakumar et al. [42, 45] claimed that ventricular fibrillation can be induced in even larger animals weighing up to 50 kg. However, in their studies the animals were

given epinephrine shortly before the electric exposure, a drug that is known to significantly reduce the ventricular fibrillation threshold.

Computer simulation research considering the cardiac effects of CEW

Computer simulation models are generally limited by the validity of their software and by the computing capacity, the accuracy of the data used and the number of variables considered. The simulation of pathophysiological reactions within the human body is based on certain fundamental selection criteria of fixed, rule-based data processing. This means that for any given scenario, only one option will be chosen by the program, even if the situation at hand demands a more complex and open approach. Normally, the design of such simulations does not appreciate statistical outliers, which can never be excluded when assessing pathophysiological human body interactions. One example is a paper by Leitgeb et al. [41]. He calculated intracardial electric current density distributions for worst-case shots for the TASER X26 device as high as 30% and an overall ventricular fibrillation risk of about 1% for Europeans and 20% for Asians. His calculations seem not to be transferable to real-life scenarios when comparing these numbers to the estimated 310,000 annual CEW field uses in the US and over 5.3 million human exposures (including training exposures) [88] with very little recorded unexpected arrest-related deaths [89].

Despite their disadvantages, computer simulations are a useful tool in trying to understand, predict and reconstruct the pathway of electrical current in the human body. Especially in areas where human studies reach their moral limits, computer simulation research has contributed to the understanding of the pathophysiological effects of CEW. These studies can be seen as the fundamental basis of the following animal and human experiments. In conclusion, the majority of computer simulations come to the conclusion that CEW, while not risk free, have a reasonable degree of safety [35, 36, 56, 90].

Human research considering the effects of CEW

For evaluation of the effect and of the exact pathophysiological mechanisms of CEW, human studies are necessary. It is only possible through the direct reactions of volunteers to capture the pathophysiological reactions in the human organism and analyse them for the assessment of real-life situations. There is a wide range of human volunteer studies devoted to different health-related aspects of CEW. Potentially life-threatening health risks such as an acute respiratory failure [22, 27], and significant effects to the neuroendocrine and sympatho-adrenergic system [18, 22, 27] as well as the central nervous system [25] have been analysed intensively. A main focus of human re-

search has been the potential possibility of electrically induced ventricular fibrillation. Even though these concerns are continuously argued in cases where the later deceased was shot at a nearby time with an electroshock distance weapon [91–95], it has not yet been possible to actually prove this theory. On the contrary, human research groups could disprove a possible link between the exposure to CEW and a clinically significant cardiovascular response [12, 13, 19–21, 23, 26, 27, 29].

To date, there is no scientific human research that could find evidence of clinically relevant pathophysiological effects during and after an exposure to a professionally applied CEW.

The effects of CEW on pacemakers and defibrillators

The possibility of a current-induced influence on implanted cardiac pacemakers and defibrillators has been intensively investigated [33, 96–99]. A relevant impairment of these devices could not be observed in any of the investigations. In a study by Haegli et al. [96], the implanted pacemaker misinterpreted the pulse of a CEW as a ventricular flicker. However, due to the too-short exposure time and consequent lack of feedback to the cardiac pacemaker, there was no reaction of the device. Lakkireddy et al. [97] and Leitgeb et al. [98] could detect a registration of the current application by the cardiac pacemaker. However, due to the short exposure time of the TASER waveform, there was no reaction or function degradation of the devices in either case. Current research suggests that wearing a pacemaker or defibrillator is not an exclusion criterion for a TASER application.

Limitations

Our comparative analysis on animal, human and computer research is limited by the listed journals in the search engine PubMed. The evaluation of CEW use in real-life police encounters is limited by the restricted transferability of experimental research data. The operational use of CEW in law enforcement is not as carefully controlled as in an experimental set-up, making appropriate use of the device significantly more variable.

Conclusion

All use of force carries certain risks for the opponent. In the case of CEW, the cardiovascular risk is still the most controversially discussed. It is directly related to the dart-to-heart distance, which is generally too large to be of risk for an exposed healthy adult.

Some experimental animal data support the possibility of application of CEW energy to initiate cardiac capture and potentially life-threatening ventricular arrhythmia. However, the majority of current scientific medical research and, in particular, human research

data on health risks of CEW conclude that a professional use of CEW, within the guidelines proposed by the manufacturer on a healthy adult, has a reasonable harm.

In the case of a CEW exposure, all possible health risks should be excluded. Therefore, a complete medical check-up including cardiac examination with control of common cardiovascular parameters as well as a neurological observation is advised.

In cases of potential TASER-related deaths, a forensic autopsy should be performed. In addition, all medical factors as well as background information that could be associated with the event must be collected and analysed. Only then it is possible to fully confirm or disprove a true causal relationship.

Conflict of interest This paper is a result of literature search, which was not funded. S.N. Kunz is a member of the scientific medical advisory board of Axon Int. (fka TASER). J. Adamec declares that he has no competing interests.

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