

# Taser Blunt Probe Dart-To-Heart Distance Causing Ventricular Fibrillation in Pigs

Jiun-Yan Wu, *Student Member, IEEE*, Hongyu Sun, *Member, IEEE*, Ann P. O'Rourke, Shane M. Huebner, Peter S. Rahko, James A. Will, and John G. Webster\*, *Life Fellow, IEEE*

**Abstract**—The maximum distance between the heart and a model Taser stimulation dart, called the dart-to-heart distance, at which the Taser can directly cause ventricular fibrillation (VF), was measured in pigs. A 9-mm-long blunt probe was advanced snugly through the surrounding tissues toward the heart. Five animals [pig mass =  $61.2 \pm 6.23$  standard deviation (SD) kg] for ten dart-to-heart distances where the Taser caused VF were tested. The dart-to-heart distances where the Taser caused VF of the first stimulation site ranged from 4 to 8 mm with average  $6.2 \text{ mm} \pm 1.79$  (SD) and of the second stimulation site ranged from 2 to 8 mm with average  $5.4 \text{ mm} \pm 2.41$  (SD). The results help inform the evolving discussion of risks associated with Tasers.

**Index Terms**—Electrical safety, electromuscular incapacitating device, fibrillation, safety, stun gun, Taser, ventricular fibrillation (VF).

## I. INTRODUCTION

ELECTROMUSCULAR incapacitating devices (EMDs), also called electromuscular disruption devices (EMDs), human electromuscular incapacitation (HEMI) devices, and conducted electrical weapons (CEWs), such as the Taser, have been adopted by law enforcement authorities to reduce the use of guns. However, some suggest that EMDs can kill [1]. They suggest that the EMD directly electrocutes the heart, ventricular fibrillation (VF) would cause the heart to stop pumping, the blood pressure would decrease precipitously, and cardiac arrest would occur quickly. Nonetheless, many deaths following EMD use occur much later and may be caused by drug overdose, positional asphyxia, or other causes [2].

Investigators attempting to model and/or measure the likelihood that EMDs might cause VF encounter many difficulties, including variable susceptibility of individuals, variance of animal models from humans, and exceptionally challenging nu-

merical simulation models even for a standard torso. Recently Holden *et al.* [3] used extensive numerical modeling of the torso, experimental measurements of the current needed to cause VF in guinea pig isolated hearts, and concluded that the evidence argued against arrhythmogenic action of Taser devices. However, it is known that inducing sustained VF in small animals is difficult and impossible for some stimulus paradigms [4]–[6], justifying the need for considering data from larger animals, such as the live pig, more similar to humans, despite the obvious increases in experimental complexity.

We have published one report suggesting a small but estimatable risk by extrapolating from susceptibility of pigs to VF caused by an EMD-like probe [7]. The key measure was the maximum distance from the heart to the tip of the electrode probe at which the current from a Taser induced VF. This distance, which we term the dart-to-heart distance where the Taser caused VF, was  $17 \text{ mm} \pm 6.48$  standard deviation (SD) for the first VF event for a particular pig and  $13.7 \text{ mm} \pm 6.79$  (SD) for the successive VF events. However, in this experimental setup, the probe was inserted into a bluntly dissected pathway that was filled with conductive gel to exclude air, but which unintentionally permitted a more direct electrical pathway to the heart that likely increased the dart-to-heart distance where the Taser caused VF. Here, we report on parallel measurements but with an improved and more realistic experimental setup. The results refine our previous estimates and provide new data that should assist the community in evaluating the dangers of EMD devices. All experiments were approved by the appropriate Institutional Animal Care and Use Committee and adhere to all applicable laws and standards of the National Institutes of Health (NIH) and the United States Department of Agriculture (USDA) as well as the policies of the American Physiological Society (APS).

## II. MATERIAL AND METHODS

Two specially designed probes were used, both with a core conductive rod 0.8 mm in diameter to match the Taser dart diameter. The 100-mm-long skin-to-heart-distance-testing probe [see Fig. 1(a)] measured the skin-to-heart distance at the stimulation site. The 50-mm-long blunt probe [see Fig. 1(b)] delivered the Taser current. The surface of the blunt probe was insulated except for the first 9 mm portion, which delivered the stimulation current. The blunt probe was designed to match the structure of standard Taser darts except that the normally sharp tip was made blunt to avoid inadvertently piercing the heart, which would have ended the test. A conducting lead connected to X26 Taser delivered stimulation current to the pig. The

Manuscript received April 11, 2007; revised August 5, 2008. First published July 15, 2008; current version published December 17, 2008. This project was supported by the National Institute of Justice, Office of Justice Programs, U.S. Department of Justice, under Grant 2004-IJ-CX-K036. *Asterisk indicates corresponding author.*

J.-Y. Wu and H. Sun are with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA.

A. P. O'Rourke was with the Department of Surgery, University of Wisconsin, Madison, WI 53792 USA. She is now with the University of Wisconsin Hospital, University of Wisconsin, Madison, WI 53792 USA.

S. M. Huebner is with the Department of Nutritional Sciences, University of Wisconsin, Madison, WI 53706 USA.

P. S. Rahko is with the Department of Medicine, University of Wisconsin, Madison, WI 53792 USA.

J. A. Will is with the Department of Animal Health and Biomedical Sciences and the Department of Animal Sciences, University of Wisconsin, Madison, WI 53706 USA.

\*J. G. Webster is with the Department of Biomedical Engineering, University of Wisconsin, Madison, WI 53706 USA (e-mail: webster@engr.wisc.edu).

Digital Object Identifier 10.1109/TBME.2008.2002154

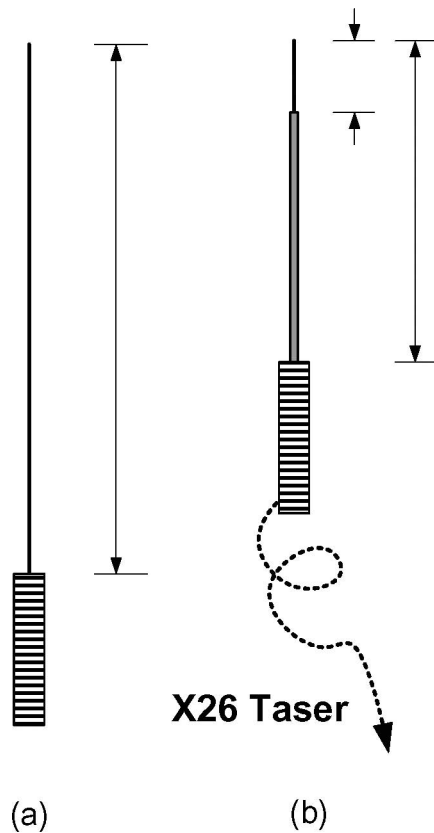


Fig. 1. (a) Distance-testing probe measured the skin-to-heart distance. (b) Blunt probe delivered the stimulation current from the exposed 9-mm-long wire.

stimulation current delivered by the X26 Taser contained peak current pulses of about 2 A for a duration of about 150  $\mu$ s and lasted about 5 s with 15–19 pulses/s.

The anesthetization process, animal monitoring method, and defibrillation procedure remained the same as in our previous animal study [7]. The pigs were premedicated with Telazol<sup>®</sup> for immobilization. Isoflurane was administered via a mask to induce a surgical plane of anesthesia. A tracheostomy was performed and placement of the endotracheal tube allowed connection to a Harvard respirator. The tidal volume was set to 15–20 ml/kg body weight. Isoflurane was set at 5% for induction and decreased to 3% to 4% when the surgical plane was achieved. The level of anesthesia was monitored by heart rate, end-tidal CO<sub>2</sub> and testing the corneal reflex, jaw tone, and limb withdrawal. If any of these reflexes were elicited, the concentration of anesthetic was increased until the response subsided. Animals were euthanized with intracardial injections of a saturated solution of KCl while under anesthesia.

Once the pharmacologic procedures were complete and the animal was in a homeostatic condition, the stimulation sites were determined. Since the midpoint of the right ventricle is known to be the most excitation-sensitive region of the heart [8], the first stimulation site, site 1, was chosen on the right thorax above the right ventricle between the third and fourth ribs, and the second site, site 2, between the fourth and fifth ribs. A shallow 2 mm wide skin incision was made only to get through

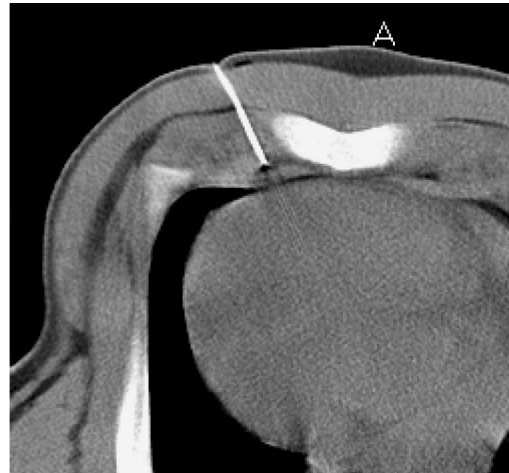


Fig. 2. Computed tomography image of blunt probe, sternum, and rib (white), lung (dark) surrounding the heart (gray). The blunt probe was inserted through the fat layer, the muscle layer, and the intercostal muscle layer between the ribs.

the tough skin. Then, the distance-testing probe was inserted through the fat layer, muscle layer, intercostal muscle layer to reach the pericardium to determine the skin-to-heart distance. It penetrated snugly through these layers. The insertion depth was determined by feeling the mechanical heart contraction behavior through the distance-testing probe. The whole process was designed to minimize the disturbance of the natural anatomical structure. After the skin-to-heart distance was measured, the skin-to-heart-distance-testing probe was carefully removed from the stimulation site.

Two stimulation darts, the blunt probe and the remote dart, delivered stimulation current. The blunt probe was slid through the previously made stimulation site track. The remote dart, a standard Taser probe, was placed on the abdominal surface at a typical Taser separation, 54 cm caudal from the blunt probe. Fig. 2 shows the relation between the blunt probe and the heart. As a preliminary study indicated that the probe had to be closer than 10 mm to cause VF, the initial insertion depth was to a distance 12 mm from the surface of the heart. After each Taser stimulation, the ECG was verified to check if the heart was beating normally. If the heart beating was normal, the dart-to-heart distance where the Taser caused VF was decreased by 2 mm and stimulation was applied again. The process continued until the first VF occurred, after which the pig was immediately defibrillated. After the defibrillation, a 5-min recovery period returned the pig to a homeostatic condition. The same experimental procedure was then applied at nearby site 2. Finally, a necropsy was carried out on the thorax of the subject to record the stimulation sites.

### III. RESULTS

Five animals [pig mass = 61.16 kg  $\pm$  6.23 (SD)] were used resulting in ten measurements of dart-to-heart distance for first inducing VF, as summarized in Table I. The skin-to-heart distance of site 1 ranged from 42 to 51 mm with average 46.2 mm  $\pm$  3.7 (SD), and the skin-to-heart distance of site 2 ranged from 45

TABLE I  
EXPERIMENTAL PARAMETERS AND RESULTS OF FIVE ANIMAL TESTS

Pig	Mass (kg)	Site 1		Site 2	
		Skin-heart distance (mm)	VF distance (mm)	Skin-heart distance (mm)	VF distance (mm)
1	58	51	5	57	7
2	68.8	49	6	45	4
3	53	45	8	47	8
4	65.6	42	4	45	2
5	60.4	44	8	45	6
Ave	61.16	46.2	6.2	47.8	5.4
SD	6.23	3.7	1.79	5.2	2.41

to 57 mm with average  $47.8 \text{ mm} \pm 5.2$  (SD). The dart-to-heart distance where the Taser caused VF of site 1 ranged from 4 to 8 mm with average  $6.2 \text{ mm} \pm 1.79$  (SD), and the dart-to-heart distance where the Taser caused VF of site 2 ranged from 2 to 8 mm with average  $5.4 \text{ mm} \pm 2.41$  (SD). All animals remained physiologically stable throughout the experimental procedures; however, blood pressures were depressed after the first episode of VF. The necropsy showed that all sites were on the right ventricle.

#### IV. DISCUSSION

The five animal experiments yielded ten dart-to-heart distances where the Taser caused VF in anesthetized pigs for the X26 Taser stimulation current and a probe modeling the Taser. The basic result is that the average dart-to-heart distance where the Taser first caused VF at site 1 was  $6.2 \text{ mm} \pm 1.79$  (SD), which is significantly different (Wilcoxon rank sum test,  $p$ -value = 0.0077) from our previous report [ $17 \text{ mm} \pm 6.48$  (SD)] [7]. The reduction clearly indicates that the previous procedure in which conductive gel filled the bluntly dissected pathway, substantially increased the distance at which VF could be induced, presumably by reducing the resistance of the pathway from dart to heart.

Roy *et al.* [8] suggested that the most sensitive region of the heart for external stimulation is close to the midpoint of the right ventricle. This region was under the third and fourth ribs above the heart that was identical to our first stimulation site 1. We compared the dart-to-heart distance where the Taser caused VF for site 1 and site 2, between the fourth and fifth ribs, to see if there was a significant change. The dart-to-heart distance where the Taser caused VF at site 2 was slightly smaller  $5.4 \text{ mm} \pm 2.41$  (SD), but not significantly different (Wilcoxon rank sum test,  $p$ -value = 0.67).

This is the fourth study known to the authors in which the X26 Taser has been shown to be capable of inducing VF in a pig. In addition to this and our previous report, Nanthakumar *et al.* [9] placed subcutaneous darts parallel to the skin of pigs and administered epinephrine as a continuous intravenous infusion at a dose of  $0.1\text{--}0.7 \text{ g}/(\text{kg}\cdot\text{min})$  titrated to increase the animal's heart rate to a 50% increase from the baseline before discharges. They obtained VF for 1 X26 discharge in 16 for a dart-to-heart distance where the Taser caused VF of about 45 mm. Dennis *et al.* [10] exposed pigs to two prolonged 40 s X26 discharges. They obtained VF for two out of six experi-

mental pigs for a dart-to-heart distance where the Taser caused VF of about 45 mm. While [7], [9], and [10] all showed larger dart-to-heart distance where the Taser caused VF in pigs, we believe that the procedures used here to prepare the pig were least disturbing of the four and hopefully most accurate.

As noted in the introduction, we believe that there is need to balance measurements on isolated hearts of small animals with measurements on live larger animals in order to further the scientific debate on the issue. We also note that eight humans out of 150 have skin-to-heart distances of 17 mm or less [7], and thus, if a dart were to penetrate the full 9 mm at the most sensitive location, would be within the range at which live pigs experience VF in our study. This important and contentious area is in need of further work to clarify the risks.

#### REFERENCES

- [1] Amnesty International [Online]. Available: <http://news.amnesty.org/index/ENGAMR510392006>
- [2] D. Manojlovic, C. Hall, D. Laur, S. Goodkey, C. Lawrence, R. Shaw, S. St-Amour, A. Neufeld, and S. Palmer, "Review of conducted energy devices," Canadian Assoc. Chiefs Police, Ottawa, ON, Canada, Tech. Rep. TR-01-2006, 2005 [Online]. Available: <http://www2.taser.com/research/science/documents/canada%20safety%20report.pdf>
- [3] S. J. Holden, R. D. Sheridan, T. J. Coffey, R. A. Scaramuzza, and P. Diamantopoulos, "Electromagnetic modelling of current flow in the heart from TASER devices and the risk of cardiac dysrhythmias," *Phys. Med. Biol.*, vol. 52, pp. 7193-7209, 2007.
- [4] L. A. Geddes, "The small heart and the critical mass for ventricular fibrillation," *IEEE Eng. Med. Biol. Mag.*, vol. 23, no. 1, pp. 196-197, Jan.-Feb. 2004.
- [5] R. A. Malkin, J.-N. Eynard, and N. F. Pergola, "Extended cardiac tachyarrhythmias in guinea pigs," in *Proc. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 1997, pp. 387-388.
- [6] R. A. Malkin and A. de-J. Curry, "Frequency dependence of the cardiac threshold to alternating current between 10 Hz and 160 Hz," *Med. Biol. Eng. Comput.*, vol. 41, pp. 640-645, 2003.
- [7] J.-Y. Wu, H. Sun, A. P. O'Rourke, S. Huebner, P. S. Rahko, J. A. Will, and J. G. Webster, "Taser dart-to-heart distance that causes ventricular fibrillation in pigs," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 3, pp. 503-508, Mar. 2007.
- [8] O. Z. Roy, J. R. Scott, and G. C. Park, "60-Hz ventricular fibrillation and pump failure thresholds versus electrode," *IEEE Trans. Biomed. Eng.*, vol. BME-23, no. 1, pp. 45-48, Jan. 1976.
- [9] K. Nanthakumar, I. M. Billingsley, S. Masse, P. Dorian, D. Cameron, V. S. Chauhan, E. Downar, and E. Sevapsidia, "Cardiac electrophysiological consequences of neuromuscular incapacitating device discharges," *J. Am. Coll. Cardiol.*, vol. 48, pp. 798-804, 2006.
- [10] A. J. Dennis, D. J. Valentino, R. J. Walter, K. K. Nagy, J. Winners, F. Bokhari, D. E. Wiley, K. T. Joseph, and R. R. Roberts, "Acute effects of TASER X26 discharges in a swine model," *J. Trauma*, vol. 63, pp. 581-590, 2007.



**Jiun-Yan Wu** (S'99) received the B.S. degree in agriculture machinery engineering and the M.S. degree in applied mechanics from the National Taiwan University, Taipei, Taiwan, R.O.C., in 1999 and 2001, respectively, and the second M.S. degree in electrical and computer engineering from the University of Wisconsin-Madison, Madison, in 2006.

During his graduate studies in Taiwan, he was engaged in research on microelectromechanical systems (MEMS) involving optical metrology system design and thin film characterization. After obtaining his M.S. in 1999, he began research in electromuscular incapacitating device safety involving ventricular fibrillation characteristic, electrophysiology, and constellation catheter measurement at the University of Wisconsin. His current research interests include medical instrumentation development, signal processing, and electrophysiology measurement.

**Hongyu Sun** (S'99–M'06) received the B.Eng. and M.Eng. degrees in telecommunications engineering from Beijing University of Posts and Telecommunications, Beijing, China, and the first M.S. degree in statistics and the second M.S. and Ph.D. degrees in electrical and computer engineering from the University of Wisconsin-Madison, Madison, in 2007.



**Ann P. O'Rourke** received the B.S. degree from Emory University, Atlanta, GA, in 1993, and the M.D. and Masters' degrees in public health from the University of Wisconsin, Madison, in 2002 and 2006, respectively.

She is currently a Resident in General Surgery and Surgical Oncology Research Fellow at the University of Wisconsin Hospital, University of Wisconsin.

**Shane M. Huebner**, photograph and biography not available at the time of publication.



**Peter S. Rahko** received the College Graduate degree from the St. Olaf College, Northfield, MN, in 1975, and the Graduate degree in medicine from the Medical School, University of Minnesota, Minneapolis, in 1979.

He is currently an Associate Professor of Medicine in the Cardiovascular Medicine Division at the University of Wisconsin, Madison, where he has been since 1985. He is also the Director of the Adult Echocardiography Laboratory at the University of Wisconsin Hospital. In 1985, he completed his cardiology fellowship at the University of Pittsburgh. He was a Resident in Medicine at Indiana University, Indianapolis, where he is engaged in clinical practice in all aspects of echocardiography. He has major teaching responsibilities and also clinical research responsibilities connected with the echocardiography laboratory. He provides consultative care in end-stage heart disease, transplantation evaluation, and advanced pharmaceutical and device therapies for heart failure. His current research interests include echocardiography and advanced heart failure.



**James A. Will** received the B.S. degree in animal husbandry, the M.S. degree in animal husbandry-genetics from the University of Wisconsin, Madison, in 1952 and 1953, respectively, the D.V.M. degree in veterinary medicine from Kansas State University, Manhattan, in 1960, and the Ph.D. degree in comparative cardiology from the University of Wisconsin, in 1967.

He is a Professor Emeritus of Veterinary Medicine, School of Veterinary Medicine (SVM), Surgery, Medical School, Biomedical Engineering, College of Engineering (COE), and Animal Science, College of Agricultural and Life Sciences (CALS) at the University of Wisconsin. He teaches cardiovascular and renal physiology to undergraduate and graduate students and is involved with assisting in the biological training of graduate students in biomedical engineering. His current research interests include the development of devices for hepatic tumor ablation.



**John G. Webster** (M'59–SM'69–F'86–LF'97) received the B.E.E. degree from Cornell University, Ithaca, NY, in 1953, and the M.S.E.E. and Ph.D. degrees from the University of Rochester, Rochester, NY, in 1965 and 1967, respectively.

He is a Professor Emeritus of Biomedical Engineering at the University of Wisconsin-Madison. He is the Editor of the most-used text in biomedical engineering *Medical Instrumentation: Application and Design* (New York: Wiley, 2009, 4th ed.). He is also the author or coauthor of 22 other books including the *Encyclopedia of Medical Devices and Instrumentation* (New York: Wiley, 2006, 2nd ed.) and 200 research papers. In the field of medical instrumentation, he teaches undergraduate and graduate courses in bioinstrumentation and design. He is also involved in improving electrodes for ablating liver to cure cancer, safety of electromuscular incapacitating devices, and a miniature hot flash recorder.

Dr. Webster is a Fellow of the Instrument Society of America, the American Institute of Medical and Biological Engineering, and the Institute of Physics. He is also a member of the IEEE-Engineering in Medicine and Biology Society (EMBS) Administrative Committee and the National Institutes of Health (NIH) Surgery and Bioengineering Study Section. He was the recipient of the 2001 IEEE-EMBS Career Achievement Award.