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Ventricular Fibrillation Threshold of Rapid Short Pulses

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Abstract:

The risk of VF (ventricular fibrillation) from continuous AC utility (50/60 Hz) power has been well quantified and is reflected in accepted standards. Similarly, the required charge for a single pulse delivered during the T-wave of the ECG is also quantified. However, there are no studies that deal with the VF risk of a train of multiple short pulses such as those used in electric fences and conducted electrical weapons (CEWs). We studied 5 swine with an electrode placed through the anterior chest such that the tip was 10 mm from the epicardium. A return electrode was attached remotely to the lower abdomen. Five-second trains of 100 µs pulses at rates of 10-70 PPS (pulses per second) were delivered with gradually increasing charges until VF was induced. The VF threshold was also determined for 60 Hz AC current. As expected, the VF charge threshold decreased with increasing rates. For pulse rates between 10-30 PPS, the aggregate current (= charge • pulse rate) was constant at the VF threshold. The VF threshold in terms of AC RMS current was 7.4 ± 1.9 times the aggregate current VF threshold for the rapid short pulses. These results may have utility for setting safety standards for electric fences and for CEWs such as TASER® CEWs. This also allows for the risk assessment of CEWs by comparison to international electrical safety standards. The output of these weapons appears to be well below the VF risk limits as set by these standards.

INTRODUCTION:

The risk of ventricular fibrillation (VF) from continuous AC utility (50/60 Hz) power has been quantified (by RMS current) and is reflected in accepted standards.[1] Similarly, the required charge for a single pulse delivered during the T-wave of the ECG is well quantified. However, there are no studies that deal with the VF risk of a train of multiple short pulses. There are safety standards for electric fences but the supporting studies, if any, are not identified.[2-4] A data-supported model quantifying the risk of VF for rapid short pulses would have utility for setting safety standards for the electric fence and the conducted electrical weapon (CEW) such as a TASER® CEW.[5]

METHODS:

The protocol was approved by the IACUC for the University of Alabama at Birmingham. Swine weighing 20-25 kg were initially anesthetized with telazol/xylazine (4.4 mg/kg) and intubated. An arterial line was inserted for pressure measurements and an electrogram catheter was inserted into the right ventricle. The animals were anesthetized with isoflurane (1-3% inhalation). Arterial blood gases and electrolytes were measured every 30 – 60 minutes.

An adjustable probe assembly (Figure 1) was placed in an intercostal space directly over the right ventricle. The probe was advanced under fluoroscopy until the tip was 10 mm from the epicardium. The polarity was defined as the polarity at this probe. A remote return electrode was placed in the lower abdomen.

Figure 1. Adjustable depth current delivery probe.

A custom waveform generator was used that can generate rectangular pulses of varying durations, pulse rates, and charges or voltages. The pulse duration was fixed at 100 µs as that is a common pulse width for both the CEW and the electric fence.[3, 6] The pulse rate was set at 10, 15, 20, 25, 30, 50, and 70 Pulses Per Second (PPS). This covered the 15-25 PPS rates used in existing CEWs.[6, 7]

A randomized sequence of pulse rates was used and the initial polarity was also randomized. Pulses were delivered for 5 seconds and the output was increased in 0.1 log voltage (26% increase) steps until VF was induced. The delivered pulse charge was then noted. The VF threshold (VFT) was defined as this pulse charge required for induction.

After VF induction, animals were defibrillated immediately and allowed 5 minutes for recovery. The pulse rates were then repeated for the opposite polarity. At the beginning and end of each study, 60 Hz sine-wave current was delivered at increasing currents until VF was induced. That current was measured as an RMS (root-mean-square) value and defined the AC VFT.

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RESULTS:

As shown in Figure 2, the electrical charge at the VF threshold (VFT) varied from ~1.6 mC (millicoulombs) down to ~ 0.2 mC for a range of 8:1 over the pulse rate range of 7:1.

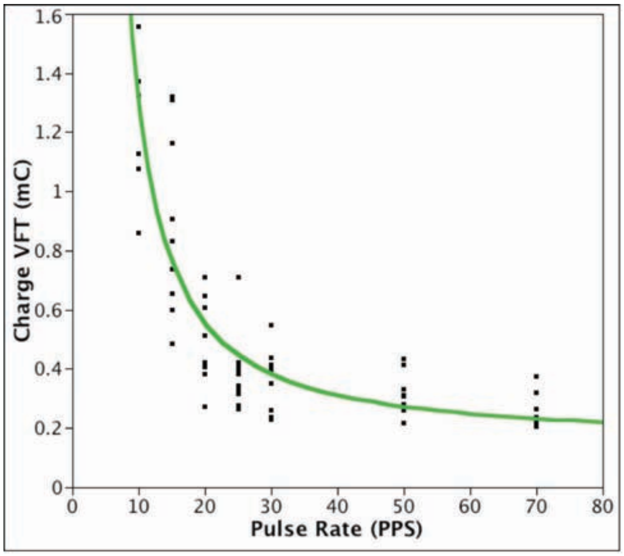

Figure 2. The VFT charge decreased with pulse rate.

The impedance was 159 ± 13 Ω which is less than the 602 Ω reported for the shorter standard CEW probe shown in Figure 3 due to the greater penetration.[6]

Figure 3. Typical CEW probe with 9 mm dart.

The VFT results are also shown in Table 1 for both anodal (+) and cathodal (-) pulses (polarity of the electrode close to the heart). The mean charge is the average of the VFT charge across the 5 animals.

The aggregate current is defined as:

I_{agg} = pulse charge × pulse rate

For example:

2 mA = 100 µC × 20 PPS

The aggregate current was calculated for the mean charge at the VFT for each pulse rate and is shown in the last column. This varied from 8 to 20 mA for a range of 2.5:1. The aggregate current VFT for anodal stimulation was 25% less on average than for cathodal stimulation. While cathodal stimulation is more efficient at low rates these results are consistent with the anodal dip phenomenon seen for stimulation at high rates.[8-10]

Table 1. Grouped VFTs.

Polarity	PPS	Mean Charge (µC)	Stdev (µC)	Aggregate Current (mA)
+	10	1028	161	10
-	10	1305	16	13
+	15	772	256	12
-	15	1016	335	15
+	20	437	120	9
-	20	536	138	11
+	25	318	79	8
-	25	458	167	11
+	30	321	125	10
-	30	432	96	13
+	50	281	60	14
-	50	333	77	17
+	70	232	21	16
-	70	280	80	20

The aggregate current VFTs for each polarity and pulse rate were normalized for each animal to reduce biological variability. This was done by averaging the aggregate current VFT in each animal. Each individual VFT value was then divided by this (animal specific) average and the result was multiplied by the 13.24 mA average for all animals. These normalized results are shown in Figure 4.

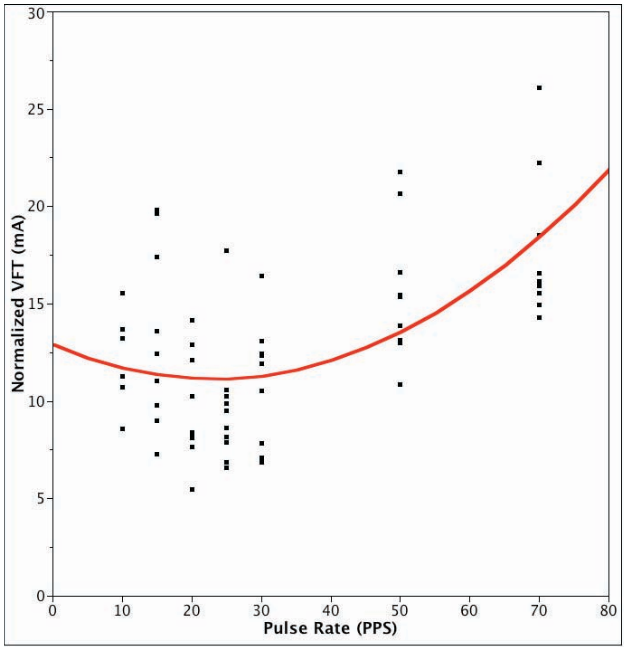

Figure 4. The aggregate current VFT is constant for pulse rates of 10-30 PPS.

The quadratic fit shown was statistically significant (p = .026 for the squared term) and the overall fit had $r^2 = .33$.

The aggregate current VFT appeared to be constant for pulse rates from 10-30 PPS. This was evaluated with a paired T-test as shown in Table 2. To obtain a very conservative test for similarity, we elected not to use a repeated-measures statistical test or a Bonferroni correction. There was no difference between the *aggregate current* VFTs at 10, 15, 20, 25, and 30 PPS. The 50 PPS VFT was higher than that of 30 PPS (p = 0.02). The 70 PPS VFTs was also higher than that for 30 PPS (p = 0.0005).

Table 2. Aggregate currents (mA) at VFT for all swine.

PPS	1	2	3	4	5	Mean	P vs. next faster rate
10		11.3	5.4	10.9	14.6	10.6	0.39
15	7.3	9.4	16.6	18.6	11.8	12.7	0.34
20	10.9	9.2	8.4	6.9	12.5	9.6	0.97
25	12.3	10.2	8.8	8.4	8.3	9.6	0.14
30	11.6	12.4	13.1	9.9	8.8	11.2	0.02
50	12.4	16.0	17.4	14.3	16.8	15.4	0.09
70	16.1	15.4	21.3	18.3	17.0	17.6	

The anodal and cathodal aggregate current VFTs were averaged for each animal and compared to the averaged AC RMS VFTs as seen in Table 3. The AC VFT was not available for animal #3. The average ratio between the AC RMS and aggregate current VFT (for the pulse trains) was 7.4 ± 1.9.

Table 3. Comparison of aggregate current to AC RMS VFT.

Subject Number	1	2	3	4	5
VFT (aggregate current mA)	13.6	15.1	13.2	13.1	11.2
VFT (mA RMS AC)	125	130		67.5	69.5
Ratio	9.21	8.59		5.16	6.20

DISCUSSION:

We believe that this is the first quantitative determination of the ability of rapid short pulses to induce VF. We believe that this is also the first comparison of the ability of rapid short pulses to induce VF to that of AC utility power current.

It is well accepted in the scientific community that the fundamental metric of cardiac capture capability (for short pulses) is the electronic charge.[11, 12] This has not been appreciated by some in the standards community as their standards are essentially based on the RMS current. This is understandable for sine-wave utility power as that is the source of the vast majority of non-lightning electrocutions.[13]

Mazer et al found that delivering electrical charge into the cardiac T-wave sufficient to induce VF took a mean of 19 J (joules) with external patches which corresponds to an electrical charges of about 100 mC.[14] Swerdlow had a patient (unpublished) that he induced with only 1 J which (assuming typical capacitances) corresponds to about 20 mC of electrical charge. The value of 20 mC is also what the IEC (International Electrotechnical Commission) considers to be in the VF risk range for chest exposures.[1] Note that the 20 mC value is 200 times that of the typical 100 µC of a CEW and thus there is no risk from a single CEW pulse falling on a T-wave.

The effect of sine wave frequency on the VFT has been well studied.[15, 16] However, there are no published data on the effects of short pulses with varying pulse rates. This is the main reason why some safety standards try to approximate these types of pulse trains by phase-controlled sine waves.[1] Unfortunately, the only supporting data referenced are from VF studies using pulses of at least 5 ms duration and at rates of 100 PPS.[17] These pulses are 50 times wider than those used for electric fences and CEWs and the rate of 100 PPS is over 5 times that of a typical CEW.[7]

Calculations based on extrapolations of standards based on this data have led to estimates of VF rates from TASER CEWs in the range of 5-50%.[18, 19]

With the derived ratio of 7.4 for the equivalent AC RMS current the potential VF risk of a device using rapid short pulses can be estimated. For example the aggregate current of the popular TASER® X26™ CEW of 1.9 mA (= 100 µC • 19 PPS) can be compared to an AC source of 14.1 mA RMS. That is significantly less than the long-application VF safety level of 35 mA of international standards.[1]

CONCLUSIONS:

Over the range of pulse rates of 10-30 PPS, the capability of rapid short pulses to induce ventricular fibrillation is given by the aggregate current, which is the pulse charge multiplied by the pulse rate. The ability of rapid short pulses to induce VF is approximately equal to a 60 Hz AC current with an RMS current of 7.4 times the aggregate current of the rapid short pulses.

This allows for the risk assessment of conducted electrical weapons by comparison to international electrical safety standards. The output of these weapons appears to be well below the VF risk limits as set by these standards.

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