Transthoracic Cardiac Stimulation Thresholds for Short Pulses

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***Introduction* — The most common cause of death due to electric shock is ventricular fibrillation (VF). This work reviews applicable results from the literature and provides an estimation model for the risk of VF with short-duration pulses.**

***Methods and Results* — For 1 ms pulses, the predicted current and charge thresholds required for successful transthoracic cardiac stimulation were 1.12 A and 1.12 mC, respectively. For pulses of 0.1 ms durations, the transthoracic current and charge thresholds predicted by the model are 10.9 A and 1.09 mC, respectively.**

***Conclusion* — In humans, the charge required for single-response cardiac capture using transthoracic electrodes and 0.1 ms pulses is at least 0.5 mC. The transthoracic charge required to trigger repetitive ventricular responses in humans is at least several times higher than that for single responses. Hence, in adult humans, the transthoracic charge threshold required to induce repetitive ventricular responses, tachycardia, or fibrillation, with 0.1 ms pulses is expected to be significantly greater than 1 mC.**

I. Introduction

The most common cause of death due to electric shock is ventricular fibrillation (VF). Significant research efforts have been dedicated to studying VF thresholds [1 – 5]. However, most of the focus has been on the effects of 50/60 Hz alternating currents (AC) [1, 6] or of pulses of over 10 ms duration [7 –9]. There has been less emphasis on studying the effects of current pulses of durations shorter than 1 ms. With the advent of devices such as transcutaneous electrical nerve stimulators (TENS), functional electrical stimulators (FES), and conducted electrical weapons (CEW), it is important to have a closer look at the effects of current pulses of short durations [10 – 12]. This work reviews applicable results from the literature and provides an estimation model for the risk of VF with short-duration pulses.

II. Review of relevant transthoracic stimulation studies

Zoll *et al*. conducted a clinical trial on 134 patients using their Noninvasive Temporary Pacemaker (NTP) [8]. The NTP maximum output current was a rectangular pulse of 140 mA and 40 ms duration, for a maximum charge per pulse of 5.6 mC. Transthoracic stimulation thresholds required to trigger single cardiac responses were measured in 6 intervals: < 46 mA, 46 – 60 mA, 61 – 80 mA, 81 – 100 mA, 101 – 140 mA and non-responders [8]. The results are summarized in Table I, where the midpoints of the above current intervals are listed. Zoll *et al*. reported that thresholds for repetitive responses, tachycardia, or fibrillation were 5 –16 times the thresholds for single responses [13]. Such ratios far exceed the maximum output of the NTP. Moreover, pacing in demand-mode further increased the threshold for repetitive responses. For the sake of patients' comfort, clinical stimulation was adjusted to levels just above threshold for single responses [8].

Clinton *et al*. studied the efficacy of transthoracic cardiac pacing on patients who presented to emergency departments with asystole or various forms of bradycardia [14]. They used a Zoll NTP with output currents of up to 140 mA and fixed 40 ms durations. Out of 37 patients, there were 11 survivors. There were 6 that responded to the pacing protocol and had their blood pressure increased. The remaining 5 survivors were non-responders. The average pacing current was 76 mA, or 3.04 mC/pulse, in the 6 responders, and 96 mA, or 3.84 mC/pulse, in the 5 non-responders [15].

Falk *et al*. reported their preliminary experience with the Zoll NTP on a group comprising 16 healthy volunteers and 14 patients who required temporary pacing due to their clinical conditions [15]. Fifteen volunteers and 13 patients tolerated transthoracic stimulation up to levels that produced single-response cardiac capture. No ventricular tachycardia (VT) or VF episodes were reported [15]. The average pacing threshold in volunteers was 54 mA. Patients had an average pacing threshold of 56 mA.

TABLE I. Current and charge thresholds for transthoracic pacing.

Reference	N [subjects]	Duration [ms]	Current [mA]	Charge [mC]
[14]	6	40	76	3.04
	5	40	96	3.84
[8]	22	40	23	0.92
	41	40	53	2.12
	23	40	71	2.82
	6	40	91	3.62
	10	40	121	4.82
[16]	15	40	54	2.16
	13	40	56	2.24
[18]	2	10	50	0.50
	9	10	100	1.00
	10	10	200	2.00
[17]	16	40	63	2.52
	19	40	53	2.12
	21	40	51	2.04
[19]	8	40	67	2.66
	5	20	72	1.44
	5	20	80	1.60
	5	20	86	1.72
	4	20	104	2.08
[20]	9	1	4875	4.88
	28	1	4626	4.63

Falk *et al*. reported failure to pace —despite stimulation with maximum output of the device —in a single patient with severe dilated cardiomyopathy [15, 16]. Due to the patient's cardiomyopathy, even transvenous pacing was possible only with currents greater than 4 times the normal pacing threshold

[16]. They concluded that although this situation was very uncommon, caution was warranted in patients with extensive chronic myocardial disease, as they may exhibit elevated pacing thresholds.

Béland *et al*. analyzed external pacing efficacy in 56 pediatric patients age 0.9 – 17 years using 40 ms pacing pulse durations [17].

Berliner *et al*. assessed the safety and efficacy of transthoracic temporary pacing in 21 patients undergoing elective surgical procedures [18]. The pacing threshold was 50 mA in 2, 100 mA in 9 and 200 mA in the remaining 10 patients. Pacing thresholds were lower with 20 ms pulse durations. However, in 19 of the 21 patients complete capture was achieved with a pulse width of 10 ms. Patients were monitored for a day following the procedure, but there were no reports of arrhythmias of any type induced by the transthoracic pacing.

Heller *et al*. compared the functions of 5 different types of external pacemakers in 10 patients [19]. One pacemaker type had output current pulses with a duration of 40 ms. The other types used output pulses of 20 ms duration. As shown in Table I, the capture thresholds ranged from 66.5 mA (2.67 mC), with the 40 ms pulse, to 104 mA (2.08 mC) with 20 ms duration pulses. No complications or inadvertently-induced cardiac arrhythmias were reported.

Sharma *et al*. analyzed 2 modalities of inducing VF in patients implanted with cardioverter-defibrillators (ICD) [20]. Such patients must undergo a VF-induction procedure in order to determine their defibrillation thresholds (DFT) and to adjust the ICD output accordingly. One of the methods they studied involved delivery of a pulse shock during the vulnerable period of the T wave. The shock-on-T pulse had a duration of 1 ms. For successful VF induction in women (n = 9), the average pulse magnitude was 215 V. In men (n = 28), the average pulse magnitude was 204 V. The lead impedance at high voltages (i.e. over 100 V) was measured at an average of 44.1 Ω [19]. These values were not used in our strength-duration model.

Table II summarizes the total number of patients (pts), pulse duration, average capture current, and average capture charge for the data presented in Table I.

TABLE II. Average thresholds as a function of pulse duration.

Total N pts	Duration [ms]	Avg. Current [mA]	Avg. Charge [mC]
37	1	4687	4.69
21	10	143	1.43
19	20	85	1.69
205	40	59	2.37

If reported, the size of the thoracic electrodes used for the pacing procedures was in the same range, approx. 100 – 150 cm^2, for all studies summarized in Table II (with the exception of Sharma *et al*., who used intracardiac electrodes). For example, there were 205 patients who were paced successfully with pulses of 40 ms duration. The successful pacing current and charge thresholds, averaged over N = 205 patients, were 59.2 mA and 2.37 mC, respectively. Data at 10 and 20 ms pulse durations were also summarized, respectively. The average intracardiac VF current and charge thresholds for the patients studied by Sharma *et al*. are shown in the first row of Table II [20]. These data were included for reference purposes and are discussed in the next section.

III. Predictive Model for Stimulation with Short-Duration Transthoracic Pulses

1. *Strength-duration model for transthoracic cardiac stimulation.*

In order to predict cardiac capture thresholds for pulses of short duration, we developed a strength-duration model based on data shown in Table II. We used the well-known, empirical Weiss-Lapicque model [21, 22]. Figure 1 illustrates the current, charge and energy curves. The current, I, equals:

$$I = b\,(1 + c/d) \tag{1}$$

whereas the charge, Q, required for successful stimulation is:

$$Q = bc + bd \tag{2}$$

b and c are the rheobase and chronaxie, respectively [21 – 23]. The pulse duration equals d.

In order to determine parameters b and c, data from Table II was used. A best-fit program was used to find b and c that minimized the mean square errors with respect to reported average current thresholds for durations of 10, 20 and 40 ms.

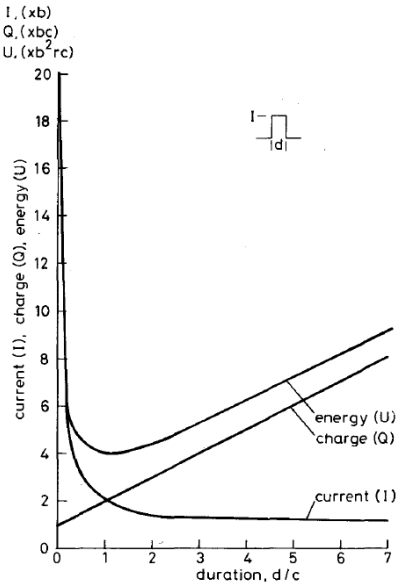

Fig. 1. The strength-duration curve according to the Weiss-Lapicque model [21 – 23].

2. *Predicted transthoracic cardiac capture threshold for pulses with durations of 0.1 and 1 ms.*

Using the charge model (2), a minimal mean square error of 1.6% was determined for b = 32 mA and c = 34 ms. Table III presents the computed current and charge thresholds vs. those reported in Table II.

TABLE III. Computed pacing thresholds at short pulse durations.

Duration [ms]	Reported I [mA]	Computed I [mA]	Reported Q [mC]	Computed Q [mC]
0.1	N/A	10912	N/A	1.09
1	N/A	1120	N/A	1.12
10	142.9	140.8	1.43	1.41
20	84.5	86.4	1.69	1.73
40	59.2	59.2	2.37	2.37

Although an estimated chronaxie of 34 ms seems unrealistically long, the model provides estimated thresholds consistent with existing research. For 1 ms pulses, the predicted current and charge thresholds required for successful transthoracic cardiac stimulation were 1.12 A and 1.12 mC, respectively. These thresholds were about 4 – 5 times lower than those reported by Sharma *et al*. for shock-on-T VF induction [20]. As discussed above, Zoll *et al*. reported that thresholds for repetitive responses, tachycardia, or fibrillation were 5 – 16 times the thresholds for single responses [4, 13]. Therefore, the thresholds predicted by this model fall within expected ranges.

For pulses of 0.1 ms durations, the transthoracic current and charge thresholds predicted by the model were 10.9 A and 1.09 mC, respectively. As discussed in more detail in Section IV, these thresholds were consistent with data presented by Walcott *et al*. [24]. In a small-swine model, Walcott *et al*. determined an average VF threshold of 1.2 mC when stimulating with percutaneous electrodes, 0.1 ms pulses and 10 pulses per second (pps) [24]. Swine are known to have a higher susceptibility for VF induction than humans [1 – 3]. Accounting for the low weight and high VF susceptibility, the Walcott data corroborated the single-response charge thresholds predicted above for 0.1 ms duration pulses.

In order to understand worst-case scenarios, we estimated the minimum charge needed for cardiac capture. For this purpose, we tuned the strength-duration charge model from Section II using the lower end of the current thresholds reported in Table I. The number of points was lower (N = 33 pts) than when using the averages from Table I (N = 245 pts). As such, the confidence in the results from the tuned model was lower as well. We obtained a mean square error of 0.5% at a rheobase b = 38 mA and a chronaxie c = 17 ms. This estimated chronaxie, while still long, was closer to the expected less-than 10 ms range. These findings indicated that the longer chronaxie of 34 ms estimated on the complete patient dataset may have been the result of outliers, larger variability among cited studies, or cellular activation accommodation. Table IV summarizes the results.

TABLE IV. Pacing thresholds for tuned model.

Duration [ms]	Computed I [mA]	Computed Q [mC]
0.1	6498	0.65
1	684	0.68
10	100	1.02
20	72	1.41
40	53	2.16

IV. Discussion

The transthoracic cardiac capture thresholds predicted above were based on averages of the data presented in Table I. In Table II, the model predicted that, on average, transthoracic pulses with duration of 0.1 ms require approximately 1 mC of electrical charge in order to consistently trigger single cardiac responses. As shown in Table IV, even when using the lower end of the current thresholds from Table I to tune our model, the charge required for successful induction of single cardiac responses was approximately 0.65 mC.

Zoll *et al*. reported that the current required to induce VF in dogs was 12 times the capture threshold when 1 ms pulses were used. The ratio VF/capture increased to 25 for pulse durations of 2 or 3 ms. Although the ratio decreased at longer durations, it remained greater than 5 [4]. In humans, Zoll *et al*. reported that thresholds for repetitive responses, tachycardia, or fibrillation were 5–16 times the thresholds for single responses [13]. Fig. 2 summarizes data presented by Voorhees *et al*. and shows high ratios between VF and capture thresholds [25]. Consistent with results presented by others, Voorhees *et al*. computed this ratio to equal 12.6 [4, 13, 26]. A regression model based on data from Fig. 2 estimated that a charge threshold of at least 0.16 mC was required to induce single-response cardiac capture in dogs using 0.1 ms pulses. In order to induce repetitive ventricular responses, tachycardia, or fibrillation, in dogs, the regression model predicted that at least 1.9 mC would be needed. Grimes *et al*. reported lower charge levels for single-response cardiac capture in humans [27]. However, those thresholds apply to the specific conditions used in the study that Grimes *et al*. cited [27, 28]. In the actual study, conducted by Zoll *et al*., the authors implanted needle electrodes into patients' myocardium via a thoracotomy procedure [28]. As such, while providing important data, the report by Grimes *et al*. does not apply to thresholds required for transthoracic cardiac capture.

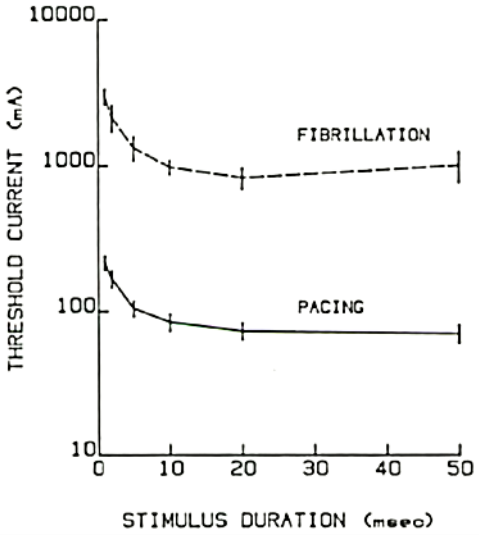

Fig. 2. Pacing and fibrillation thresholds in dog [25].

Other factors may affect VF thresholds. Horowitz *et al*. have shown that coronary artery disease can lower VF thresholds [29]. They applied current to the epicardial surface of either the right or left ventricle with a bipolar probe.

Patients with 75% obstruction of the left anterior descending coronary artery had an average left VF threshold of 18.6 mA, significantly lower than the normal average value of 33.6 mA [29]. However, Swerdlow et al found that cardiomyopathy patients do not have lower VF thresholds [30].

The repetition rate of narrow pulses may also affect VF thresholds. In a study conducted on small swine, anesthetized with isoflurane, Walcott *et al*. have shown that the charge required for inducing VF with 0.1 ms pulses dropped from 1.6 mC at 10 pps to 0.28 mC at 70 pps [24].

V. Conclusion

The analyses presented above show that in humans, including measurement and study variances, the charge required for single-response cardiac capture using transthoracic electrodes and 0.1 ms pulses, is at least 0.5 mC. Consistent with data presented by several other research groups, the transthoracic charge required to trigger repetitive ventricular responses in humans is at least several times higher than that for single responses. Consequently, in adult humans, the transthoracic charge threshold required to induce repetitive ventricular responses, tachycardia, or fibrillation, with 0.1 ms pulses is expected to be significantly greater than 1 mC.

VI. Disclosure

Dr. Panescu is a paid consultant to TASER International, Inc. (TASER). Dr. Kroll is a consultant to TASER, and a member of the TASER Scientific and Medical Advisory Board (SMAB) and Corporate Board. Mr. Brave is an employee of TASER and legal advisor to the TASER SMAB and Training Advisory Board.

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