Current density and electrically induced ventricular fibrillation[1,2]

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STARMER, C. FRANK, AND ROBERT E. WHALEN *Current density and electrically induced ventricular fibrillation.* Med. Instrum. 7: 158–161, 1973. Ventricular fibrillation was electrically induced in dogs and humans. Current density (J_S) at the electrode surface was calculated, and relative magnitudes of current density (J_i) within the heart were approximated from measurements of fibrillatory currents and voltages, respectively. Variations in J_S and J_i were compared in order to determine which better defined the fibrillation threshold in electrically induced ventricular fibrillation. When applying fibrillatory current with varying sized electrodes, the current density (J_S) at the surface of the heart which induced fibrillation increased with decreasing electrode size, while the approximate internal current density (J_i) inducing fibrillation remained virtually unchanged. That internal current density remains practically constant and thus determines the current threshold of ventricular fibrillation is compatible with the concept that a critical number of myocardial cells or critical mass of tissue must be excited in order to maintain fibrillation.

current density; electricity; ventricular fibrillation; heart; electric shock

Editor's Note: Drs. Starmer's and Whalen's article, published in the January-February 1973 issue of Medical Instrumentation, *contained errors that developed during the publication process. The microampere symbol appeared in several places where the milliampere symbol should have been used, which altered the measurements of this significant article. The article is correctly reprinted here with the apologies of the Managing Editor and his editorial staff.*

Introduction

Several investigators (2,3) studying the effects of electric current on the heart have suggested that the current density or concentration of current in the heart is one of the primary determinants of the threshold of electrically induced ventricular fibrillation. However, little has been done to explore and substantiate these suggestions.

Current density, J, can be considered as a measure of the concentration of current. While current is the movement of electrical charges per unit time, current density is the concentration of these charges as they move through a region. In order to evaluate the role of an applied current density as a determinant of ventricular fibrillation thresholds, two current densities can be defined. The first current density, J_s, exists at the surface where the electrodes contact the heart. This current density is expressed as:

$$J_s = I/A \qquad (1)$$

where A is the electrode surface area in contact with the heart and I is the current "crossing" this area.

The second current density, J_i, is a current density existing within the heart and may be expressed as:

$$J_i = \sigma E \qquad (2)$$

where σ is the electrical conductivity within the heart and E is the electric field intensity within the heart. Because the electric field intensity (E) cannot be readily measured in the intact functioning heart, the average current density within the heart (J_i) can be more usefully described by the approximation:

$$J_i = \sigma V/D \qquad (3)$$

where V is the voltage applied to the conducting media and D is the distance between the two electrodes where the voltage is applied.

In order to evaluate the role of current density in defining ventricular fibrillation thresholds and to determine the most appropriate concept for understanding the role of current density, ventricular fibrillation was electrically induced in dogs with varying sized electrodes placed on the heart. Fibrillatory currents and voltages were measured and current densities at the electrode surface (J_S) were calculated. Analysis of voltages associated with the onset of fibrillation permitted a comparison of current densities within the heart (J_i). Similar studies were then performed in humans during open heart surgery. These parallel studies were also designed so that human and dog ventricular fibrillation thresholds could be compared under similar conditions.

Methods and Results

Dog studies. Six mongrel dogs ranging in weight from 13 to 20 kg were anesthetized with intravenous pentobarbital sodium (30 mg/kg of body weight). After endotracheal intubation, respiration was maintained with a positive pressure respirator. The fem-

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oral artery was cannulated and arterial pressure was recorded by means of a Statham P23Db pressure transducer coupled to an Electronics for Medicine photographic recorder, which was also used for continuous electrocardiographic monitoring.

After a right thoracotomy was performed, the pericardium was opened to allow the application of various sized electrodes to the heart. Three pairs of stainless steel disc electrodes 2 mm thick (large = 5.06 cm^2, medium = 1.13 cm^2, small = 0.05 cm^2) were used to apply current to the heart. These were placed as matching pairs near the cardiac apex and the right ventricular outflow tract.

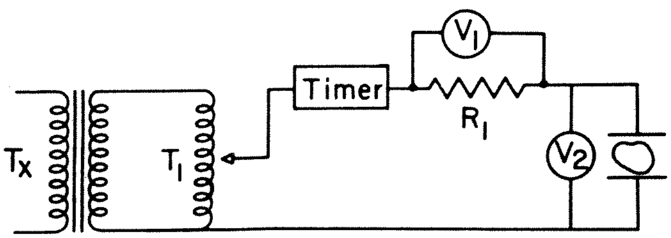

FIG. 1. Circuit for applying and measuring fibrillatory voltages and currents. Transformer T_x isolates the apparatus from the power lines. T_1 is a variable autotransformer used to adjust the voltage applied to the heart. The timer controls the time duration of current flow. The voltmeter V_1 measures the voltage across R_1, from which the applied current is determined. V_2 measures the voltage across the heart.

In each dog a series of at least five determinations of the current (60 Hz) and the voltage required to induce ventricular fibrillation with each pair of electrodes were obtained. The order of application of the different sized electrodes was randomized. Currents and voltages were applied and measured utilizing the apparatus illustrated in Figure 1 and described in previous reports. Hewlett-Packard model 403-B voltmeters and a model W-2 Variac were used. Alternating current was applied through the electrodes placed on the myocardial surface. The duration of current application was fixed at 2 seconds so that the fibrillation threshold measurement would occur at the approximate diastolic excitation threshold (10). This measurement would then approximate the lower limit for the ventricular fibrillation threshold.

Multiple episodes of ventricular fibrillation were induced in each dog and immediately converted to normal sinus rhythm by an internal DC countershock. At least 5 minutes elapsed between fibrillation episodes in order to allow the heart to stabilize.

Immediately following the terminal fibrillation in each dog, the conductivity of the heart was measured. The four-electrode method was used (8) and a mean value of 3.80×10^{-3} ohm^{-1} cm^{-1} $\pm .02$ (± 1 SD) was determined from the six dogs.

Table 1 indicates the mean fibrillatory currents (I), voltages (V), and current densities at the heart surface (J_S) in each of the six dogs using the three different pairs of electrodes. The threshold currents and electrode surface areas were used for calculating J_S. The current necessary to induce ventricular fibrillation increased with the electrode size. The trend of increasing current with increasing electrode size was confirmed statistically by analyzing the threshold current for varying electrode sizes utilizing the analysis of variance and the Scheffe test of contrasts (9) (large vs. medium, $P<.05$; large vs. small, $P<.0001$; medium vs. small, $P<.0001$). There was very little overlap in the threshold current data for different sized electrodes in any one dog. The same threshold current for different sized electrodes was noted only nine times during the course of 175 fibrillations.

Although the mean threshold current changed nearly tenfold (.34 milliamperes (mA) for small electrodes to 2.99 mA for large electrodes), the threshold voltages within each dog remained almost constant regardless of electrode size. This pattern of large differences in current and small differences in voltage is emphasized in Figure 2, which summarizes the data from dog No. 3.

TABLE 1. *Currents, voltages, and current densities at the heart-electrode surface associated with ventricular fibrillation in dogs*

	Large Electrode (5.06 cm^2)			Medium Electrode (1.13 cm^2)			Small Electrode (0.05 cm^2)		
Dog	Voltage	Current	Current density at surface	Voltage	Current	Current density at surface	Voltage	Current	Current density at surface
	v	*mA*	*mA/cm²*	*v*	*mA*	*mA/cm²*	*v*	*mA*	*mA/cm²*
1	.505±.123	3.46±1.00	.683	.609±.156	1.57±.35	1.21	.436±.133	.303±.030	6.10
2	.485±.113	3.33± .75	.658	.438±.081	1.49±.41	1.15	.430±.211	.725±.206	14.50
3	.393±.036	2.91± .67	.575	.394±.052	1.12±.13	.86	.365±.071	.207±.079	4.10
4	.351±.060	2.29± .87	.453	3.47 ±.042	.95±.06	.73	.300±.024	.117±.015	3.50
5	.324±.023	2.67± .20	.527	.473±.036	1.33±.07	1.02	.407±.060	.284±.031	5.72
6	.438±.111	3.25± .86	.642	.556±.132	1.29±.60	1.00	.334±.081	.340±.116	6.71
Mean	.416	2.99	.593	.469	1.29	.995	.378	.340	6.73

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Unlike the threshold currents, the current densities at the surface of the heart (J_S) associated with ventricular fibrillation varied inversely with the electrode size, i.e., the larger the electrode, the smaller the current density (J_S) needed to induce fibrillation. There was a tenfold change in current density (J_S) between large and small electrodes.

Human studies. To facilitate the repair of intracardiac lesions, ventricular fibrillation was purposely induced in patients during open heart surgery as suggested by Glenn et al. (1) and Levy and Lillehei (4). The same apparatus used in the animal studies was used to induce ventricular fibrillation and measure the required voltage and current levels. One pair of electrodes identical in size and shape to either the small, medium, or large dog electrodes was placed at the cardiac apex and right ventricular outflow tract. All patients were on total cardiopulmonary bypass and under moderate hypothermia (30 to 34C°). A total of eight patients were fibrillated with the large electrodes (5.06 cm^2), six with the medium electrodes (1.13 cm^2), and six with the small electrodes (0.05 cm^2). The need to minimize delay in the operative procedure and the desire to avoid repeated defibrillations made multiple determinations of the current and voltage thresholds in each patient impractical.

TABLE 2. *Currents, voltages, and current densities at the heart-electrode surface associated with ventricular fibrillation in humans*

Electrode Size	Patient Number	Voltage	Current	Current Density at the Surface (J_S)
		v	*mA*	*mA/cm²*
Large (5.06 cm^2)	1	.24	1.50	.296
	2	.50	2.10	.415
	3	.40	2.60	.513
	4	1.25	4.00	.790
	5	1.00	4.00	.790
	6	1.60	6.00	1.180
	7	—	4.00	.790
	8	—	2.30	.454
Mean		.83	3.31	.653
Medium (1.13 cm^2)	9	.60	1.80	1.353
	10	.80	1.10	.827
	11	—	1.10	.827
	12	.40	.75	.564
	13	.40	.80	.602
	14	—	1.50	1.128
Mean		.55	1.18	.883
Small (0.05 cm^2)	15	.50	.25	4.940
	16	.10	.18	3.550
	17	.75	.40	7.900
	18	.62	.30	5.390
	19	.89	.24	4.740
	20	.27	.20	3.950
Mean		.52	.26	5.080

Comparison of the threshold currents from Table 2 indicates that the same trend observed in the dog studies were present in the human studies. There was a decrease in threshold current with a decrease of electrode size. This trend was also confirmed statistically. The differences in the current thresholds for the various electrode sizes were all highly significant ($P<.0001$). As noted in the animal studies, the current density (J_S) that was associated with ventricular fibrillation varied inversely with the electrode size. A comparison of voltage levels noted with electrodes of different sizes is of questionable value because each voltage determination was made in a different heart under different conditions.

Comparison of the human thresholds with the dog thresholds indicates comparable fibrillation thresholds regardless of electrode size. With the large electrodes the average level for inducing ventricular fibrillation in humans was 3.31 mA compared to 2.99 mA in dogs. The medium sized electrodes required an average of 1.18 mA in humans compared with 1.29 mA in dogs. The small electrodes required an average of .26 mA in humans and .34 mA in dogs.

Discussion

Several investigators have stated that the density of current in the myocardium may determine the current threshold for ventricular fibrillation. If current density is a critical determinant of the current threshold for fibrillation, it should remain the same if electrodes of varying sizes are used to apply the current to the heart. Within the limits of this study, current density may be considered in terms of either a current density (J_S) calculated at the electrode surface or an internal current density (J_i) calculated within the heart.

If the current density necessary to induce ventricular fibrillation is determined by the formula for current density at the electrode surface ($J_S = I/A$), this current density should remain the same, while the applied current should decrease when electrodes of decreasing sizes are used to apply the current to the heart. This was not the case in the present studies. In the animal studies, even though the current did decrease with decreasing electrode size, there was a tenfold increase in surface current density between the large electrodes and the small electrodes. Essentially, the same results were noted in the human studies.

If the internal current density ($J_i = \sigma V/D$) is the critical factor for determining the current threshold of fibrillation, J_i should remain constant when electrodes of varying sizes are used to apply the current to the heart. The present studies indicate that such is the case. Although repeated measurements of the electrical conductivity of the media (σ) could not be made because of the complexity of the measurement in the living heart, a reasonable approximation of J_i can still be obtained. It can be assumed that for any one dog, σ does not change appreciably. Every effort was made to maintain the same electrode separation (D) in each individual dog. Thus, in any one dog, σ and D are approximately constant, and the internal current density (J_i) becomes a function solely of the applied voltage (V). If there is no change in voltage regardless of the electrode size, there has been no change in internal current density. Analysis of the voltages in Table 1, which are a reasonable approximation of internal current density, indicates that in four of six dogs the voltage thresholds for different sized electrodes in an individual dog were essentially the same. Thus, despite large differences in fibrillating current and surface current density (J_S), the approximate internal current density (J_i) was the same for different electrodes. In the remaining two dogs (1 and 6), there was a slightly greater variation. In all six dogs, the major component of the variation in voltage could reasonably be attributed to small changes in the electrode separation (D) during the repeated determinations of fibrillation thresholds.

A review of studies describing the prerequisites for developing sustained atrial fibrillation offers an explanation as to why internal current density seems to be a more critical determinant of ventricular fibrillation thresholds than surface current density.

Moe and his co-workers (5-7) have postulated that in order to maintain sustained atrial fibrillation, a critical mass or number of cells must be fibrillated. If a mass of fibrillating atrial tissue is decreased in size by progressively cutting pieces of atrial tissue away from the main mass, atrial fibrillation will cease. It has been suggested that as the mass of fibrillating tissue is progressively decreased in size, the chance of developing a single, coordinated, depolarizing wave that would terminate fibrillation is markedly enhanced.

Extension of this concept of a critical mass for sustained fibrillation from atrial to ventricular tissue offers an explanation as to why internal current density (J_i) rather than surface current density (J_s) is important in defining fibrillation thresholds. Current density at the electrode surface defines the current density in only a small area and a relatively small number of cells immediately beneath the stimulating electrodes, whereas internal current density describes the current density within an electrical field encompassing the entire heart and thus incorporates at least a critical mass of cells.

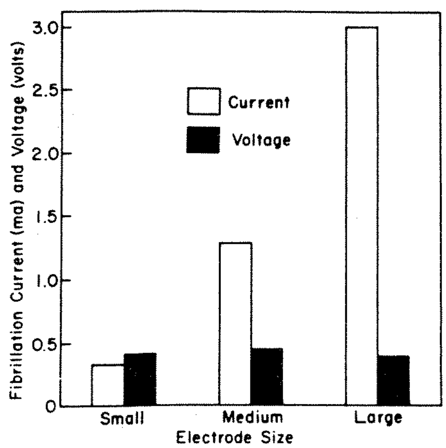

FIG. 2. The white and black bars indicate the relative changes of the currents and voltages associated with ventricular fibrillation in dog 3. For the three sizes of electrodes used, the voltage is almost constant, while the current changes by a factor of 10.

Equally important in interpreting the fibrillation-threshold data presented are the relationship between these levels of current and the levels of current required to induce ventricular fibrillation previously presented in the literature, and their relationship to the development of safety standards. Using the smallest electrodes (.05 cm² area), average currents of 260 μA for humans and 340 μA for dogs were measured. Using a similar experimental method in dogs, Weinberg (11) reported mean fibrillatory current values of 205 μA (n=20) for a current pathway between an electrode catheter in the right ventricle and a 15 cm² EKG electrode on the chest, and 162 μA (n=16) for a current pathway between an electrode catheter in the left ventricle and an EKG electrode on the chest. Minimum values of 60 and 40 μA were measured respectively. Weinberg's left ventricular data with a mean of 162 μA and a standard deviation of 30 μA indicates that approximately 95% of the observations occurred between 100 and 220 μA. His right ventricular data indicates a mean value of 205 μA and a standard deviation of 158 μA. This mean value $\pm$ 2 SD creates an interval falling below 0 μA. One must interpret this as indicating the observations were not normally distributed about the 205 μA mean value. Because the lowest measurement made with his right ventricular catheter-chest electrode path was 60 μA, many observations exceeding 205 μA must have been obtained in order to create a large apparent standard deviation. Whalen (12) reports a mean current of 258 μA (n=215) using the same experimental method in dogs. The current path was between an electrode catheter in the right ventricle and a 15 cm² EKG electrode on the chest. The range of his data was between 20 and 800 μA.

Although measurements of 20, 40 and 60 μA were occasionally observed in the above studies, these occurrences were rare and the vast majority of the current thresholds were in the 200 to 300 μA region. Whalen's mean of 258 is comparable to the 340 μA level in dogs using the .05 cm² electrodes reported in this study. Because Whalen's sample size exceeds Weinberg's by a factor of 10, it represents a better estimate of the average fibrillation threshold.

Because a relationship between electrode size and fibrillation current threshold was documented in this study, one might ask whether lower thresholds could be observed with smaller electrodes. The answer is probably yes, but the relationship of this to the problem of electrical safety standards should be questioned. Electrode catheters provide the usual vehicle for delivering electrical current to the heart. Most of these catheters have a contact area of approximately 2 $\times$ 2 mm, yielding an area of .04 cm². Therefore, one would expect the current required to induce ventricular fibrillation with an electrode catheter to be comparable with that obtained from the .05 cm² electrodes used in this study. The catheter data presented by Weinberg (11) and Whalen (12) would seem to support this conclusion. Therefore, average current thresholds in the 200 to 300 μA range measured in both animals and man would seem the logical point around which to design standards.

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