THE ROLE OF VOLTAGE, DURATION, AND ENERGY OF THE ELECTRICAL PULSE IN DEFIBRILLATION OF THE HEART

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The fact that the exposed heart can be defibrillated by electrical discharges of low capacity and high voltage (1.74 μF, 20,000 V) was demonstrated in 1900 by Prevost and Battelli [13]. Later, N. L. Gurvich established the great importance of the time factor and the role of the general principles of excitation in the phenomenon of electrical defibrillation of the heart [2-4]. In accordance with this, it was rational to include inductance in the discharge circuit in order to increase its duration and effectiveness [2]. This scheme lies at the basis of the construction of modern defibrillators.

The growth in the use of the pulse defibrillator for the treatment of various cardiac arrhythmias attaches considerable importance to the method of calibrating the electrical pulse applied to the heart. In Soviet defibrillators the duration of action is constant (8-10 msec) and close to the "temps utile" of stimulation of the heart, and the dosage is determined by the voltage of the discharge on the condenser [1, 4, 5]. In the Lown "Cardioverter" the energy and not the voltage of the pulse is graded [7, 8]. When the parameters of capacitance and voltage are combined in this concept (energy), no attention is paid to the duration of the pulse, and this may lead to serious defects in the construction of the defibrillator.

In the present investigation the relationship between the duration, voltage, and energy of the defibrillating pulse was studied. For this purpose the comparative values of the threshold voltage and of the essential quantity of energy were investigated during defibrillation of the heart by discharges of condensers of different capacitance through an inductance.

EXPERIMENTAL METHOD

Altogether 260 tests were carried out on 19 dogs weighing 8-22 kg after receiving an injection of pantopon (4 mg/kg). Ventricular fibrillation was produced by application of an alternating current of 127 V for 2 sec, through needle electrodes inserted beneath the skin of one forelimb and of the contralateral hind limb. The heart was defibrillated by the discharge of a condenser through electrodes 7-9 cm in diameter. Thd electrodes were fixed in a constant position on the right and left sides of the thorax in the line of the heart.

Discharges of condensers of the following capacitance were tested: 1.6, 2, 4, 8, 16, and 40 μF. With an inductance of 0.4 H and a resistance of about 100 Ω (30 Ω of active resistance of the coil and 70 Ω of resistance of the animal), the duration of the half-period of the pulse was 2.5, 2.8, 4, 5.6, 8.3, and 14.5 msec respectively. For measurement of the threshold value of the defibrillating voltage during the period of 20-30 sec after the onset of fibrillation, from 2 to 4 discharges were given at successively increasing voltages until a defibrillating effect was obtained. The threshold voltage for the discharge of the condenser of each capacitance was tested several times during repeated (every 10-15 min) ventricular fibrillation. The maximal voltage which was used was 6000 V. In each dog the threshold voltages were measured for the discharge of a condenser of 16 μF were measured in 16 dogs, of 40 μF in 7 dogs, of 2 μF in 13, and of 1.6 μF in only 5 (small) animals (the discharges of this capacitance were not

Relationship between Defibrillating Voltage and Energy, and Capacitance of Condenser (from results of an experiment on a dog weighing 11 kg)

	Capacitance (in μF)				
	1,6	2	4	8	16
Voltage (in V)	6 000	5 400	3 900	2 700	2 000
Energy (in W. sec)	19,2	19,3	20,0	19,5	21,3

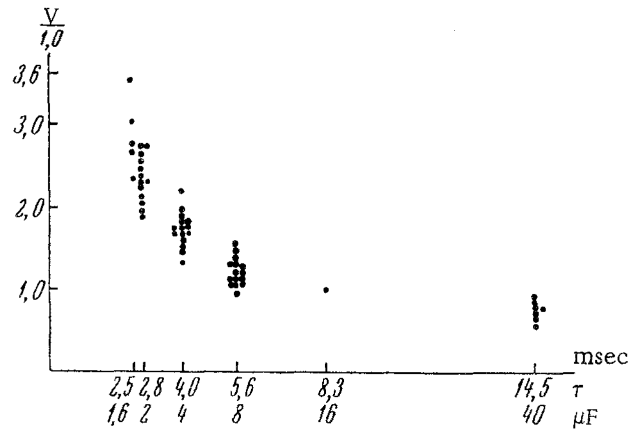

Fig. 1. Distribution of values of defibrillating voltage for different capacitances and durations of pulse from results of all experiments. Along the horizontal axis are plotted the duration of the pulse and capacitance of the discharge; along the vertical axis for each capacitance a point denotes the threshold voltage of an animal (as a ratio of the threshold at 16 μF, taken as unity).

large enough for the bigger dogs when the voltage was limited to 6000 V). When calculating the energy of the discharge through the animal, the total energy of the discharge accumulated on the condenser $(\frac{CV^2}{2})$* was divided by 3, considering the magnitude of the active resistance of the inductance coil.

EXPERIMENTAL RESULTS AND DISCUSSION

Repeated measurements of the minimal (threshold) value of the defibrillation voltage showed that it remained at a relatively constant level in all the experimental dogs for discharges of condensers of the same capacitance. For discharges of condensers of different capacitance, the magnitude of the threshold voltage diminished with an increase in the capacitance of the condenser. The relationship between the defibrillating voltage and the energy of the discharge, on the one hand, and the capacitance of the condenser, on the other (from the results of one typical experiment), is shown in the table.

A similar relationship between the defibrillating voltage and energy of the discharge and the capacitance of the condenser was observed in all the experimental dogs.

The threshold voltage in the various dogs differed depending on their weight and on other individual peculiarities. For a condenser with a capacitance of 40 μF the threshold voltage varied from 1100 to 2600 V, for one of 16 μF—from 1200 to 3200 V, 8 μF—1650 to 4600 V, 4 μF—2450 to 6000 V, and 1.6 μF—from 4300 to 6000 V.

For a fuller analysis of the data, the experimental results were treated statistically, using the "coefficient of visualization." The values of the defibrillating voltage and energy for the discharge of a condenser with a capacitance of 16 μF were taken as unity, and the voltages and energies for discharges of condensers of different capacitances were expressed as ratios of the voltages and energy for the discharge of the 16 μF condenser. The distribution of the values of the threshold voltage for discharges of condensers of different capacitances in all the animals is given in Fig. 1 from their coefficients of visualization. As Fig. 1 shows, the defibrillating voltage rose regularly with a decrease in the capacitance of the condenser, i.e., with a decrease in the duration of the pulse. For instance, it rose in relation to the threshold value for the discharge of a condenser with a capacitance of 16 μF as follows: for a capacitance of 8 μF—to 1.05-1.4, for 4 μF—to 1.3-2.1, for 2 μF—to 1.9-2.7, and for 1.6 μF—to 2.3-3.5. The voltage threshold for the discharge of a 40 μF condenser in various dogs was 0.7-0.8 of the threshold for the discharge of the 16 μF condenser. The curve showing the relationship between voltage and capacitance of the condenser (duration of the pulse) from data of the distribution of the threshold values in all the animals is given in Fig. 2 (curve V). This curve is exponential in character and is steepest in the region of small capacitances—from 1.6 to 8 μF (2.5-5.6 msec), while for capacitances of 16 and 40 μF (8.3 and 14.5 msec) it approximates to a straight line parallel to the axis of abscissas.

*C—capacitance (in F); V—voltage (in V).

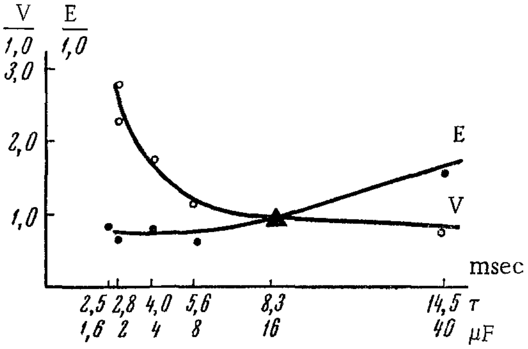

Fig. 2. Curves of the relationship between the mean values of the defibrillating voltage (V) and energy (E) and the duration of the pulse (capacitance of the discharge). Along the axis of abscissas – duration of pulse (in msec) and corresponding capacitance of discharge (in μF); along the axis of ordinates – voltage and energy (in fractions of a unit, taken as the mean value of the voltage and energy for a capacitance of 16 μF).

Comparison of the energy of the defibrillating discharge shows that the smallest values of the energy (mean 15-16 W-sec) were found with discharges of condensers of low capacitance (2, 4, and 8 μF). For discharges of condensers with a capacitance of 16 μF, the mean value of the energy was 20 W-sec. For discharges of condensers of small capacitance, the limits of variation of energy were equal in different dogs, amounting to 0.5 and 0.9 of the value of the energy for the discharge of a 16 μF condenser. The level of energy for discharges of a condenser of 40 μF capacitance was always 1.3-2 times higher than for the discharge of a 16 μF condenser. The curve showing the relationship between the defibrillating energy and the capacitance of the condenser from the data of distribution of energy in all the animals, using the coefficients of visualization as criteria, is given in Fig. 2 (curve E). Comparison of the two curves in the same figure, reflecting the relationship between the voltage and defibrillating energy, on the one hand, and the capacitance of the condenser (the duration of the pulse) on the other, shows that with a regular increase in the threshold voltage and decrease in the capacitance of the condenser, the value of the energy fell with a decrease in capacitance from 40 to 8 μF and remained at the same level for capacitance of 1.6-8 μF.

Analysis of the relationships between the voltage and capacitance of the discharges during defibrillation of the heart shows that they bear an inverse relationship to each other: with a decrease in capacitance, to obtain an effect the voltage must be increased. The curve of this relationship is exponential in character and resembles the curve reflecting the relationship between the time and strength of electrical stimulation established as a result of the classical investigations of the principles governing the excitation of the various tissues of the body [6, 7, 14]. The relationship between the defibrillating voltage and the capacitance of the condenser was studied earlier for discharges in the absence of inductance [3].

The curve thus plotted, showing the relationship between the voltage and the capacitance of the condenser for discharges through an inductance, demonstrates that the "temps utile" lies slightly outside the limits of the duration of the discharge of a 16 μF condenser (8.3 msec). However, on this flat part of the curve, the voltage rises relatively slowly, and for this reason, with a decrease in the capacitance to 8 μF (5.6 msec), the energy of the discharge falls appreciable. With a further decrease in the capacitance to 4 and 2 μF (4 and 2.8 msec respectively), the energy of the defibrillating discharge remains at the same level. It follows from these results that the choice of the optimal duration in this narrow range cannot be based on the parameter of energy, because this parameter is essentially unchanged. The parameter of voltage is more important here.

Several investigators [4, 10-12] have shown that the degree of the harmful effect of an electrical discharge on the heart is determined more by the voltage than by the duration of the discharge. Bearing in mind that the voltage is minimal when the capacitance is maximal, the conclusion is inevitably reached that, if the energy of the discharge remains equal, the optimal pulse is that with the longest duration. In the present case this corresponds to a discharge of capacitance 8 μF (5.6 msec), which defibrillates the heart at a lower voltage than discharges of smaller capacitance (4.2 μF) and possessing the same amount of energy.

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