A High-Voltage Defibrillator and the Theory of High-Voltage Defibrillation

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SUMMARY

A high-voltage capacitor defibrillator for direct as well as transthoracic defibrillation is described in the paper, together with important technical data. The theoretical reason for having an even distribution of the intensity of the electrical impulse over the entire myocardium is given. This can be achieved by using large electrodes. In experiments on dogs the dependence of cardiac arrhythmia on capacitance and voltage was studied, and thus further prerequisites for the study of defibrillation were obtained. From the preliminary results of various shapes of defibrillation impulses it was found that a capacitor discharging through an iron cored-choke seemed to be the most effective.

(1) INTRODUCTION

The control of ventricular fibrillation is a very important problem, particularly in cardiac surgery, since such surgery cannot be carried out safely without the necessary apparatus to ensure its technical success.

Much has been published on the technique of defibrillation, and it would appear that electrical methods are the most effective[2, 7, 12]. At present, two methods of electrical defibrillation are in use, namely:

(*a*) Low voltage derived by a transformer directly from the line voltage[6, 8, 14].

(*b*) High-voltage technique, using a discharge *LC* circuit[1, 3, 4, 9].

We have studied method (*b*), since high-voltage techniques have a number of advantages over low-voltage ones[10, 11]. Better results have been obtained with the high-voltage method, and this has been repeatedly confirmed in comparative studies There is also the possibility of using this technique with a closed chest.

(2) TECHNICAL DETAILS

From the results of several hundred experiments on dogs, a high-voltage defibrillator has been suggested, and the circuit diagram is shown in Fig. 1. The basic unit of the instrument is the line-voltage circuit, which contains a 16 μF capacitance and a 0·25-henry inductance. The capacitor can be charged to a voltage of 6 kV, and the defibrillation discharge is led off to electrodes through the inductance. Table 1 gives some of the electrical characteristics measured and calculated in our experiments on dogs, i.e. animals of 20–30 kg weight.

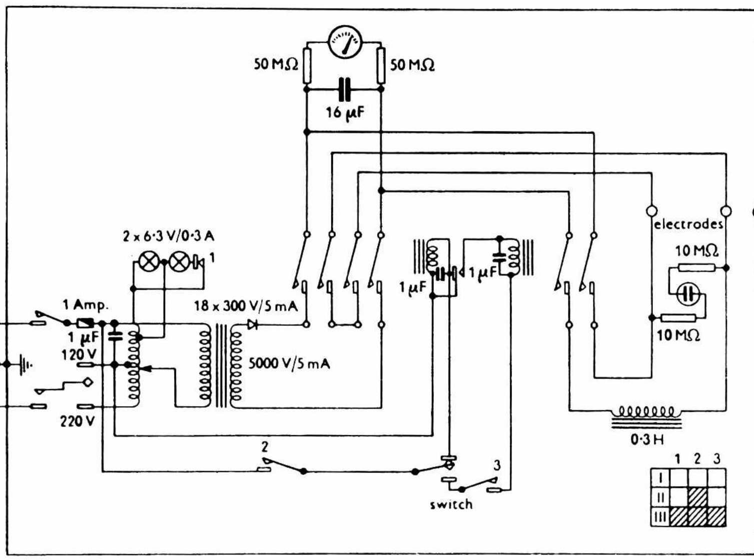

Fig. 1.—Diagram of high-voltage capacitor defibrillator.

Table 1

Averages of Electrical Values obtained in Dogs during Capacitor discharges of 1—6 kV.
C=16 μF, L=0·25 H, R= 20 ohms.

Values on capacitor		Current	Values on experimental animals		
Voltage	Energy		Voltage	Energy	Average resistance
kV	joules	amp	kV	joules	ohms
1	8	12·8	0·56	2·0	42·0
2	32	31·0	1·42	12·5	41·3
3	72	52·5	2·32	33·7	40·8
4	128	72·5	3·15	63·1	40·4
5	200	86·0	3·74	88·5	39·9
6	288	98·0	4·33	114·9	39·0

* Cardiosurgical and surgical units in Czechoslovakia are equipped with the universal defibrillator having both high-voltage and low-voltage outputs. Clinical experience has confirmed our experimental conclusions of the greater effectiveness of high-voltage defibrillation.

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The electrical energy of the capacitor charge is 8–288 joules, the discharge current is of the order of 12–98 amp and the average thoracic discharge resistance is 40 ohms. With increasing discharge voltage, the thoracic resistance decreases, by about 5% with a discharge potential of 1–6 kV. The impulse duration depends on discharge potential, and varies from 0·5 to 4 millisec, i.e. it is longer than myocardial chronaxia.

From clinical experience it is concluded that the total energy stored in the capacitor discharge required for defibrillation in normal individuals (electrodes directly on the heart) varies from 25 to 75. With a closed chest, it varies* from 50 to 250 watt-sec.

(3) BIOLOGICAL REQUIREMENTS

Successful use of the method depends on a number factors, such as the state of the myocardium and its tone, changes in the internal milieu, etc. From the technical aspect the most important factors are the size and shape of the electrodes, which determine not only the therapeutic effect of the discharge but also the degree of morphological damage to the myocardium.

It is known that during ventricular fibrillation the heart is subdivided into a large number of fibrillating segments[13]. Successful defibrillation must stimulate all myocardial fibres with a suprethreshold stimulus, bring them all into the same phase, and thus bring about synchronization of the contraction of all myocardial fibres.

It is therefore necessary for the defibrillation impulse to be subdivided evenly over the whole myocardium, so far as possible. This can be achieved by using large electrodes, and is illustrated by the following model experiment. Fig. 2 shows the distribution

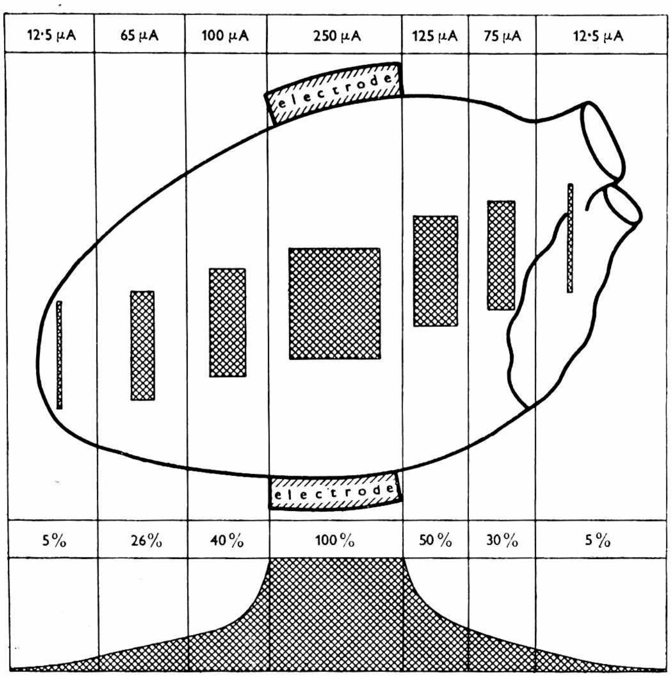


Fig. 2.—Distribution of current on the myocardium by small electrodes.

of current from small electrodes. The current density is 20 times greater between the electrodes than at the margins of the heart. This produces both morphological damage to the myocardium between the electrodes and an inadequate effect at the cardiac margins which fails to achieve defibrillation.

With adequately large electrodes (see Fig. 3), the distribution of the discharge current is much more favourable, and the cardiac margins receive up to 42% of the total current discharge between the electrodes. Thus adequate distribution of the current intensity is one of the basic conditions of successful and careful defibrillation. The requirement of large electrodes has been experimentally substantiated by Guyton *et al.*[5]

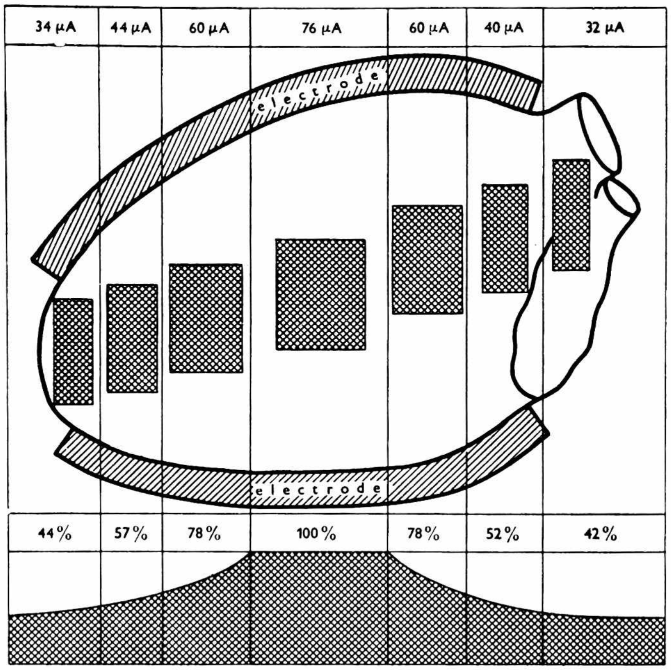


Fig. 3.—Distribution of current on the myocardium by large electrodes.

It must be realised that an electrical impulse of sufficient intensity to achieve synchronization of contraction of the myocardial fibres always produces a certain degree of morphological damage to the myocardium[15].

(4) EXPERIMENTAL RESULTS

The damage is dependent on the impulse duration, the voltage applied, the current strength and the waveform. The question of the most effective and economic impulse has not yet been satisfactorily solved. So far we have carried out 2 160 experiments on 240 dogs, in which we have observed the effect of the capacitor discharge on changes in cardiac rhythm. From the type and duration of these changes one can judge the degree of myocardial damage. We used discharges of 0·5–1 800 joules, as shown in Table 2, and Fig. 4 shows the results.

Table 2
ELECTRICAL ENERGIES IN JOULES

kV	1 μF	2 μF	4 μF	8 μF	16 μF	32 μF	50 μF	100 μF
1	0·5	1·0	2·0	4·0	8·0	16·0	25·0	50·0
2	2·0	4·0	8·0	16·0	32·0	64·0	100·0	200·0
3	4·5	9·0	18·0	36·0	72·0	144·0	225·0	450·0
4	8·0	16·0	32·0	64·0	128·0	256·0	400·0	800·0
5	12·5	25·0	50·0	100·0	200·0	400·0	625·0	1 250·0
6	18·0	36·0	72·0	144·0	288·0	576·0	900·0	1 800·0

Fig. 4 shows the relationship between abnormality of cardiac rhythm and applied electrical energy. These results permit a preliminary conclusion concerning the parameters of the defibrillation impulse. We know that maximal energy for defibrillation is up to 150 joules applied between the electrodes directly to the target organ. From the curve giving the maximal energy required for defibrillation we can read off a capacitance of

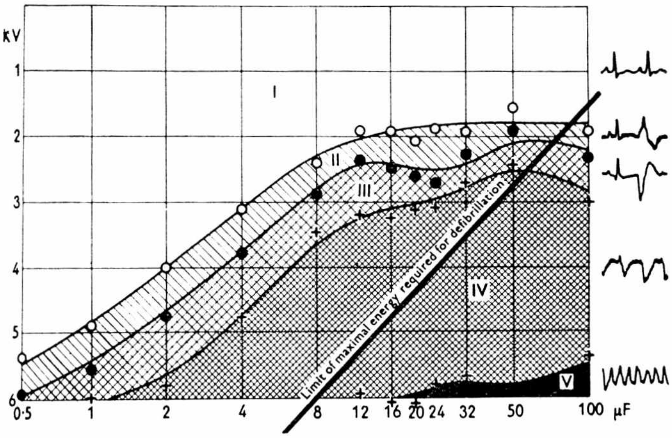
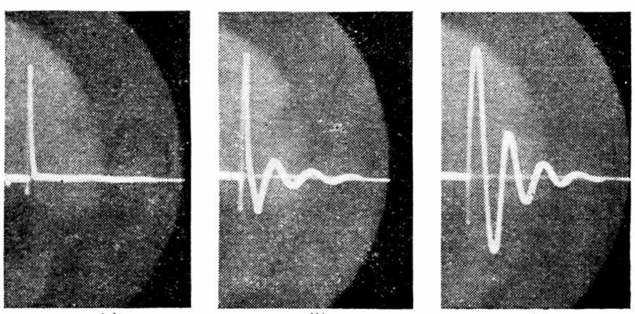


Fig. 4.—Cardiac arrhythmias following transthoracic capacitor discharges.

I. Parameters which do not produce damage.
II. Parameters which result in mild arrhythmia.
III. Parameters which result in moderate arrhythmia.
IV. Parameters which result in severe arrhythmia of long duration.
The black area indicates parameters which resulted in ventricular fibrillation.

100 μF at a potential of 2 kV. These values lie in the region without post-discharge arrhythmia, i.e. with the least degree of myocardial damage. We are therefore carrying out studies with capacitor discharge defibrillation having higher capacitance and lower voltage.



(*a*) (*b*) (*c*)

Fig. 5.—Oscillogram of various defibrillation impulses.

(*a*) Capacitor discharge $C=16\ \mu$F, $V=2{\cdot}7$ kV.
(*b*) Capacitor discharge leading through an iron-cored choke $C=16\ \mu$F, $L=0{\cdot}25$ H, $R=20$ ohms, $V=2{\cdot}7$ kVz.
(*c*) Capacitor discharge leading through a choke without iron core $C=16\ \mu$F, $L=0{\cdot}29$ H, $R=27$ ohms, $V=3{\cdot}1$ kV.

Myocardial damage depends on the voltage and electrical energy applied. The effectiveness of the defibrillation impulse depends on its shape. We therefore tried out three kinds of impulses, namely:

(*a*) Capacitor impulse leading directly to the electrodes [Fig. 5(*a*)].

(*b*) Capacitor impulse leading through an iron-cored choke [Fig. 5(*b*)].

(*c*) Capacitor impulse leading through a choke without iron core [Fig. 5(*c*)].

From our preliminary experimental results on 45 dogs, the most effective impulse is that leading through an iron-cored choke. The defibrillation threshold, expressed as the quantity of applied energy (measured on the capacitor), is the lowest in this kind of impulse. This also implies lesser myocardial damage.

The treatment of ventricular fibrillation with electrical discharge still has a number of inadequacies which result in thermal, biochemical and morphological damage to the myocardium. These changes may later cause myocardial insufficiency.

For these reasons successful defibrillation, in addition to other methods, is dependent on correct and careful application of discharge currents.

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