Cardiac Arrhythmias Following Condenser Discharges Led Through an Inductance:

COMPARISON WITH EFFECTS OF PURE CONDENSER DISCHARGES

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■ Transthoracic defibrillaton of the heart can be accomplished by several types of electric impulses, but more information is needed concerning the most suitable voltage and wave form for such impulses. In an earlier study reported in this journal,[1] we described a method of applying graded condenser discharges during selected phases of the cardiac cycle through the intact chest walls of dogs under thiopental anesthesia. The applied voltages ranged from 0.5 to 6 kilovolts, the condenser capacities from 0.5 to 100 microfarads, and the energies from 0.06 to 1800 watts. It was found that the severity of the arrhythmias caused by these discharges increased progressively as the voltage was increased, and to a lesser degree as the total amount of electrical energy was increased. Arrhythmias were significantly more severe when the shock was delivered during the refractory period (ST interval) than during the excitable stage (P-interval) of the cardiac cycle.

Work on this problem has been continued in order to find what forms of condenser discharge would produce the mildest and briefest arrhythmias. The present paper describes the effects on cardiac rhythm of condenser discharges modified by passage through an inductive resistance in series with the condenser. Such an inductance (between the condenser and the animal) changes the shape of the discharge curve; it reduces the voltage, lengthens the duration and changes the wave form (fig. 3, below). This discharge appears to be more appropriate for cardiac defibrillation;[2] but it is not known at present whether this difference of physiological effect is significant.

To answer this question several factors have been dealt with. (a) The effects of graded condenser discharges led through an inductance have been determined. (b) These effects have been compared with those of pure condenser discharges reported previously[1] with special emphasis on the relation of the induced arrhythmias to the voltage and energy of the discharge as well as to the times in the cardiac cycle at which the condenser discharges were applied. (c) The incidence of reversible and irreversible ventricular fibrillation has been related to the phase of the cardiac cycle during which the pulse was applied in order to evaluate the physiological significance of the inductive resistance in the discharge circuit.

In brief, the purpose was to determine whether a stimulus of given wave form, applied during given phases of the cardiac cycle, were particularly likely to produce fibrillation of the ventricles. Such data are important for developing safer treatment of ventricular tachycardia and auricular fibrillation by countershock.[3-6]

Methods

The present experiments were performed under pentobarbital anaesthesia (20 to 40 mg/kg body wt IV) on mongrel dogs, weighing from 20 to 25 kg. The electronic device for synchronizing the condenser discharge with selected phases of the electrocardiogram has been described previously.[1] The methods, in general, were also the same as before except that an inductive resistance (inductance 0.29 henry and resistance 27

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ohms) was connected in series with the condenser.

The capacity of the condenser was varied and the inductance was kept constant because the number of experiments necessary with a varying inductance would have made the study excessively protracted. In addition, we wished to compare our results as directly as possible with those described in the earlier paper.[1] Under our experimental conditions the interelectrode resistance (resistance of the dog's chest) was about 40 ohms. The energy loss due to ohmic resistance was therefore about 40% of the condenser energy; this reduced value represents the energy actually applied to the dog's thorax. Table 1 shows the range of energies used, corrected for ohmic losses in the inductance.

Arrhythmias were classified in the manner described previously.[1] They were divided into five groups as follows: (1) no changes of rhythm following the discharge with regular sinus rhythm afterward, (2) mild arrhythmias of brief duration, e.g., several extrasystoles, temporary tachycardia or bradycardia, (3) moderate but fully reversible arrhythmias involving longer lasting changes of rhythm such as bigeminy, ventricular extrasystoles, idioventricular rhythm, ventricular tachycardia, bradycardia, atrioventricular dissociation, etc., (4) severe changes of rhythm involving marked electrocardiographic abnormalities and ventricular arrhythmias lasting up to several minutes and producing decreases of blood pressure, and (5) severe arrhythmias changing into ventricular fibrillation.

Results

Figure 1 summarizes the incidence of the arrhythmias produced in 214 dogs by 2160 condenser-inductance discharges. The numbers at the left of figure 1 indicate kilovolts. At the bottom are shown the condensers used, ranging from 0.5 to 100 microfarads (μF). For each capacity, discharges were delivered to the heart in the three phases of the cardiac cycle, as shown at the top of the figure: viz. the absolute refractory period (ARP) labelled I in the figure; the relative refractory period (RRP) labelled II; and the excitable period (EP) labelled III in the figure.

Statistical evaluation of results obtained in all three phases of the cardiac cycle showed a difference only up to a potential of 2.5 kv. This relation is indicated by the onset of fibrillation. Whereas in ARP and EP there was no fibrillation at all, this arrhythmia was seen on 36 occasions in RRP. Between capacities of 0.5 to 2 μF fibrillation occurred between 4 and 5.5 kv. With 4 to 100 μF fibrillation occurred only from 0.5 to 3.5 kv. In the entire series of experiments we observed a transition of severe arrhythmia to fibrillation on only two occasions and this occurred with

TABLE 1

Electrical Energies, in Watts, Applied to Dogs from the Damped Condenser *

kv	0.5 μF	1 μF	2 μF	4 μF	8 μF	12 μF	16 μF	20 μF	24 μF	32 μF	50 μF	100 μF
0.5	0.03	0.07	0.14	0.29	0.6	0.9	1.2	1.5	1.7	2.3	3.6	7.2
1.0	0.14	0.29	0.58	1.16	2.3	3.5	4.6	5.8	6.9	9.3	14.5	29.0
1.5	0.32	0.65	1.30	2.61	5.2	7.8	10.4	13.1	15.7	20.9	32.6	65.3
2.0	0.58	1.16	2.32	4.64	9.3	13.9	18.6	23.2	27.8	37.1	58.0	116.0
2.5	0.90	1.81	3.62	7.25	14.5	21.7	29.0	36.2	43.5	58.0	90.6	181.2
3.0	1.30	2.61	5.22	10.44	20.9	31.3	41.8	52.2	62.6	83.5	130.5	261.0
3.5	1.77	3.55	7.10	14.21	28.4	42.6	56.8	71.0	85.3	113.7	177.6	355.2
4.0	2.32	4.64	9.28	18.56	37.1	55.7	74.2	92.8	111.4	148.5	232.0	464.0
4.5	2.93	5.87	11.74	23.49	47.0	70.5	93.9	117.4	140.9	187.9	293.6	587.2
5.0	3.62	7.25	14.50	29.00	58.0	87.0	116.0	145.0	174.0	232.0	362.5	725.0
5.5	4.38	8.77	17.54	35.09	70.2	105.3	140.4	175.4	210.5	280.7	438.6	877.2
6.0	5.22	10.44	20.88	41.76	83.5	125.3	167.0	208.8	250.6	334.1	522.0	1044.0

* Values are corrected by 40%, which represents energy loss owing to resistance (see text).

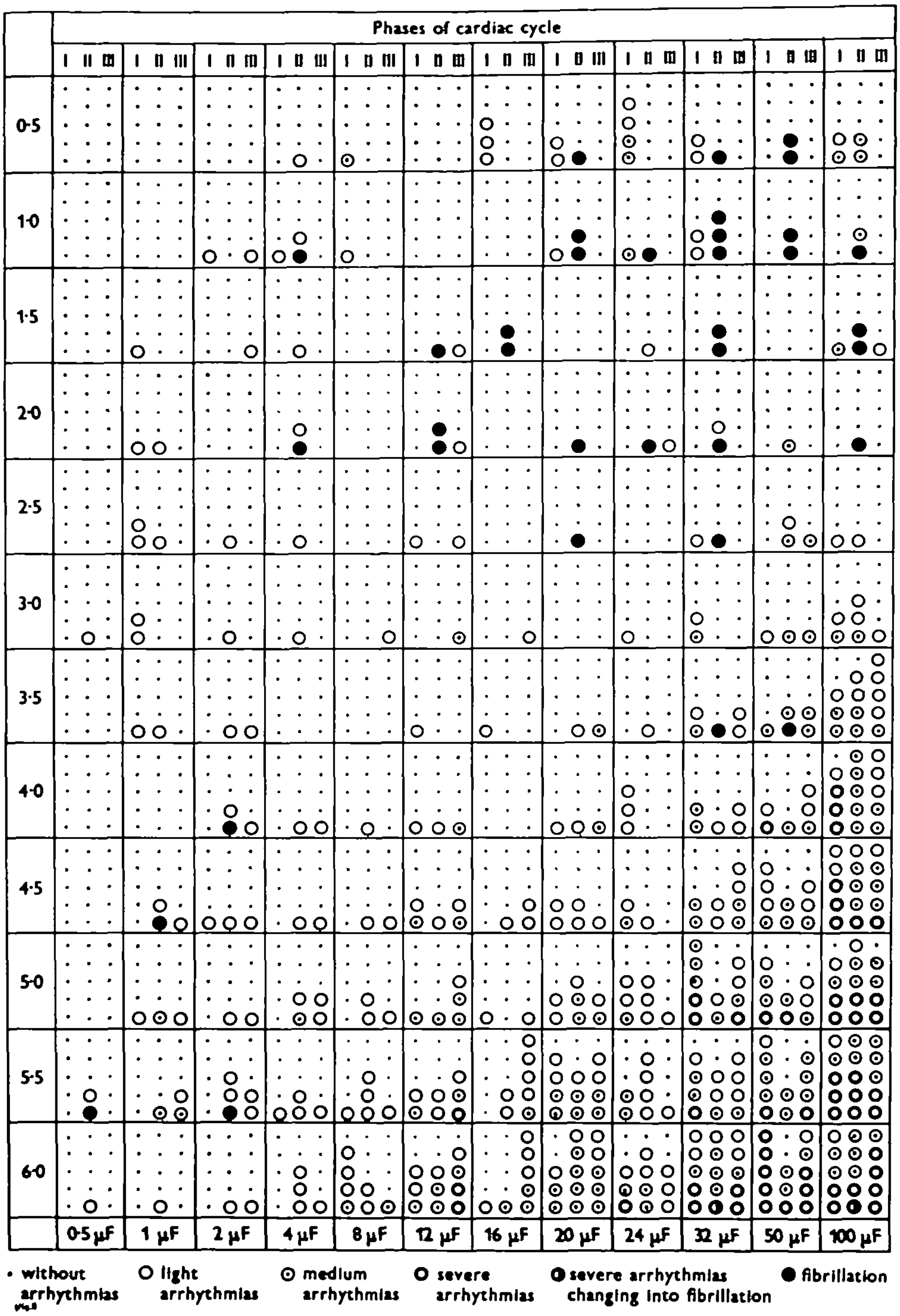


FIGURE 1

Summary of individual results in 2160 experiments using condenser discharges led through an inductance. Numerals at left indicate kilovolts. At top of figure, I indicates stimulation during the absolute refractory period (ARP), II during the relative refractory period (RRP), and III during the excitable period. At bottom of figure are shown symbols indicating nature of arrhythmias observed.

the highest voltage used (6 kv) and at capacities of 32 and 100 μF. These transitions occurred during the RRP as well.

As shown in figure 1 also, in the present experiments transitional stages to fibrillation and fibrillation itself were not dependent on voltage or condenser energy, but occurred in a random fashion throughout the distribution shown in figure 1. Fibrillation could not be evaluated therefore as a homogenous group of results.

Figure 2 evaluates all 2160 discharges without regard to the phase of the cardiac cycle. Curves of equal energy (25, 50, 100, 150 watts) are drawn in the figure and represent the reduced levels of energy actually delivered to the dogs. When compared to results from pure condenser discharges,[1] these curves are shifted to the right. The course of these curves shows that none pass over into the range of severe arrhythmia even at 6 kv. All the curves show a significant increase in thresholds for arrhythmia with respect to delivered energy. From detailed measurements of the parameters of the condenser discharge and from analysis of these data it would appear that the increased threshold is related to delivered energy rather than to voltage. The actual applied voltage is far less when an inductive resistance is inserted into the circuit.

COMPARISON OF THRESHOLDS FOR ARRHYTHMIAS PRODUCED BY PURE CONDENSER DISCHARGE AND BY CONDENSER DISCHARGE THROUGH AN INDUCTANCE WITH RELATION TO DISCHARGE ENERGY

From the practical point of view we were interested in the differences between thresholds for arrhythmia in both series of experiments, i.e., with pure condenser discharges as previously described[1] and with discharges damped by means of inductance as given in this paper. For statistical evaluation we first calculated the LD_{50} in terms of energy in

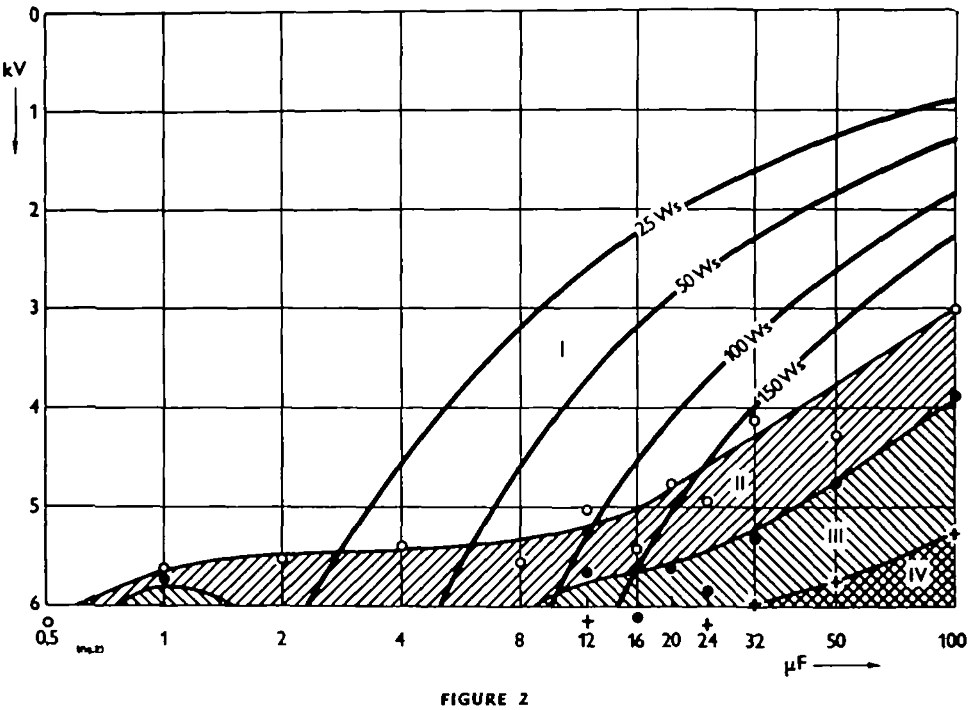


FIGURE 2

Statistical evaluation of effects on cardiac rhythm produced by condenser discharges led through an inductance. Results are plotted without regard to phase of the cardiac cycle in which the heart was stimulated. I: area without arrhythmias, II: area of slight arrhythmias, III: area of moderate arrhythmias, IV: area of severe arrhythmias. The heavy lines in the figure intersect points of identical energies (25, 50, 100, and 150 watts) with the several voltages and capacities used.

TABLE 2

Comparison of Statistical Significance of Thresholds for Arrhythmias Produced by Condenser Discharges With and Without Inductance According to Phase of Cardiac Cycle in Which Applied

Phase of cardiac cycle →		I—Absolute refractory period (ARP)			II—Relative refractory period (RRP)			III—Excitable period (EP)		
Limits of arrhythmia thresholds →		OS	SM	MS	OS	SM	MS	OS	SM	MS
Capacity in μF	0.5	—	—	—	0	—	—	—	—	—
	1.0	0	—	—	0	S	—	S	—	—
	2.0	—	—	—	0	—	—	0	—	—
	4.0	—	—	—	0	—	—	0	—	—
	8.0	S	—	—	S	—	—	S	—	—
	12.0	S	S	—	S	S	—	S	S	S
	16.0	S	—	—	S	—	—	S	S	—
	20.0	S	S	—	S	S	—	S	0	—
	24.0	S	S	—	S	S	—	S	—	—
	32.0	S	S	S	S	S	—	S	S	S
	50.0	S	S	S	S	S	S	S	S	S
	100.0	S	0	S	S	S	S	0	S	S

OS: threshold of slight arrhythmias, SM: transition of slight to moderate arrhythmias, MS: transition of moderate to severe arrhythmias, 0: no statistical significance, S: significant. Thresholds for arrhythmias are calculated with respect to energy applied.

watts according to table 1. These data were then compared statistically with data from the previous paper. As before, Körber's method of calculating LD_{50} was used with determination of upper and lower limits of 5% reliability.

Table 2 summarizes the results of this evaluation made for each of the three phases of the cardiac cycle. The table shows only whether the differences are significant or not. Zero (0) indicates absence of significant difference, S indicates that threshold was higher with inductive resistance than for unmodified condenser discharge for the same applied energy. Significantly higher thresholds are seen chiefly in the individual groups from 8 μF and higher.

RELATION OF ONSET OF VENTRICULAR FIBRILLATION TO THE SHAPE OF THE CONDENSER DISCHARGE AND TO THE PHASE OF THE CARDIAC CYCLE

Ventricular fibrillation following stimulation by a condenser discharge showed significant differences between the results of the two studies. In the first study (pure condenser discharges)[1] fibrillation occurred mainly at high voltages, with high applied energies, and rarely otherwise. Table 3 shows that a total of 108 instances of fibrillation was seen. Of this number 77 occurred directly after the discharge and 31 were preceded by some other form of severe arrhythmia. The highest incidence of fibrillation was found during the relative refractory period (RRP), i.e., 56 fibrillations or 7.7%. The least sensitive cardiac phase was the excitable period (EP) with only 2%. Fibrillation occurred, in addition, during the absolute refractory period (ARP). Other investigators have reported also that electrical stimulation during the T segment produces the highest incidence of fibrillation.

Table 3 shows also that in the present experiments (study 2, with inductive damping) the total incidence of fibrillation was only one-third that in the first study. Most fibrillations occurred at low voltages. Severe arrhythmias other than fibrillation preceded fibrillation only twice. Of 36 instances of fibrillation, representing 5% of the discharges, all occurred during the relative refractory period, i.e., when discharges were applied during the T segment.

Discussion

Answers to the question advanced in the introduction have been given already in substance under Results. There remains a need to evaluate the physiological consequences produced by the presence of an inductive resistance in the condenser discharge circuit.

It appears that this inductive damping has a marked influence on the incidence of arrhythmia. With constant values of applied energy, inductive damping was associated with a lower incidence of arrhythmia and a higher threshold for arrhythmia, as can be seen by comparing figure 2 of this paper and figure 9 of our earlier paper.[1] If we follow the curves of equal energy in figure 2, the greater portion of each lies in the region free of arrhythmia. The curves for 25 and 50 watts intersect the area of slight arrhythmias (labelled II) in the region between 5.5 and 6.0 kv. The curves for 100 and 150 watts intersect the areas of slight and moderate arrhythmias in the region between 5 and 6 kv.

For purposes of comparison consider the similarly constructed graph for results produced by pure condenser discharges published as figure 9 of the previous paper.[1] The curve for 25 watts intersected the area of slight and moderate arrhythmias up to 2 kv. The curves for 50 and 100 watts passed through the region of severe arrhythmias as well as moderate and slight arrhythmias. Only at voltages above 1.7 kv were there no arrythmias. The curve for 150 watts remained in the range of severe arrhythmia for its entire course.

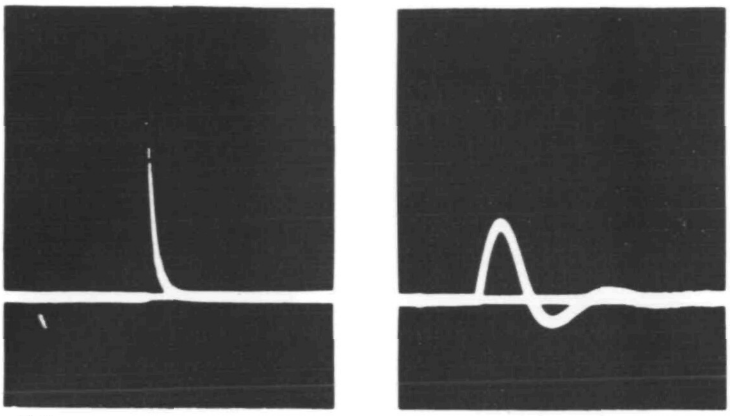
According to measurements made in this present study inductive damping of a condenser discharge changes markedly the shape of the discharge curve. The change of wave form produced by a capacity of 32 μF and a series inductance of 0.29 henry is shown in figure 3. The peak voltage is decreased and the total duration of the discharge is prolonged. Previous [1] and present results suggest that the incidence of arrhythmia depends upon discharge voltage. Dependence on discharge energy is not so clear or so marked.

A general evaluation of all results from 4320 experimental discharges indicates some of the characteristics that are desirable in a condenser defibrillator. The advantages of defibrillation by condenser discharges were emphasized in our previous work.[7, 8] Lown et al.[9] compared d-c with a-c defibrillation and concluded that the d-c method is not only more effective but also more benign for cardiac tissue. At present most d-c defibrillators contain an inductive resistance in the discharge circuit.[10–12]

TABLE 3

Incidence of Fibrillation Produced by Condenser Discharges With and Without Inductance and According to Phase of the Cardiac Cycle

	Phase of cardiac cycle								
	I—Absolute refractory period (ARP)			II—Relative refractory period (RRP)			III—Excitable period (EP)		
	Total number of discharges	Number of fibrillations	% of fibrillation	Total number of discharges	Number of fibrillations	% of fibrillation	Total number of discharges	Number of fibrillations	% of fibrillation
Study 1: Pure condenser discharge[1]	720	37	5.1	720	56	7.7	720	15	2
Study 2: Discharge led through inductance	720	0	0	720	36	5	720	0	0



(Fig.3)

A B

FIGURE 3

Oscillograms showing change in shape of discharge curve when condenser discharge is damped. A: pure condenser discharge (capacity 32 μF), B: condenser discharge (capacity 32 μF) led through an inductive resistance (inductance 0.27 henry, resistance 27 ohms).

Another question which we have kept in mind during our studies is important in the possible therapy for ventricular tachycardia and auricular fibrillation. This question deals with the relationship between the phase of the cardiac cycle and the origin of fibrillation following condenser discharges. When pure condenser discharges were used fibrillation occurred in all three phases of the cardiac cycle. This finding per se excludes this type of discharge as a therapeutic technique for cases of arrhythmia.

Although ventricular fibrillation also occurs when condenser discharges are led through an inductive resistance, it appears far less often. The principal difference is that fibrillation then occurs exclusively in the RRP, never in ARP or EP. These results based upon 2160 experiments are highly significant. They provide a theoretical basis for careful, safe therapy of cardiac arrhythmias such as ventricular tachycardia and auricular fibrillation. The incidence of these arrhythmias is much higher than that of ventricular fibrillation and their pharmacological therapy remains less than adequate.

Summary

In order to evaluate the significance of an inductance in the condenser discharge circuit of defibrillators, additional experiments were performed by methods similar to those reported previously.[1] An inductance of 0.29 henry was connected in series with the condenser. It was shown that this modification results in a much higher threshold for arrhythmias than the threshold found earlier with pure condenser discharges. The differences were highly significant and show that functional damage to the heart, evaluated by the number and severity of arrhythmias produced, is less with an inductive resistance than without it. Inductive damping reduced the incidence of fibrillation by two-thirds. In 2160 damped discharges, ventricular fibrillation occurred only 36 times, all in the relative refractory period of the cardiac cycle. Fibrillation did not appear when the discharge was applied in the absolute refractory period or in the excitable period.

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