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Cardiac Responses to Transthoracic Capacitor Discharges in the Dog

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Many previous investigators have presented data suggesting that the processes involved in excitation and recovery in heart muscle limit the "vulnerable period" to a relatively small part of the heart cycle in late systole. Evidence presented in this report indicates that there are exceptions to this rule, at least in the intact animal, since under some conditions multiple extrasystoles and ventricular fibrillation can be elicited by single stimuli of short duration and high voltage applied at almost any time in systole or diastole.

THE existence of a limited "vulnerable period" in the heart cycle, during which ventricular fibrillation can be induced by a single brief stimulus, has been amply confirmed[1,2] since the early report by King.[3] We were therefore surprised to find, while investigating the effects of capacitor shocks in the intact dog,[4] that under certain conditions ventricular fibrillation could be produced by a single capacitor discharge throughout a large part of systole and diastole. This report is concerned with a systematic investigation of this phenomenon.

Methods

The experimental animals were 21 mongrel dogs ranging in weight from 7.0 to 12.0 Kg. Animals were premedicated with morphine, 2 mg./Kg., and anesthesia was induced with open drop ether. In all animals but one a light level of anesthesia was maintained throughout the experiment by administration of an ether-air mixture through a positive-pressure respirator and endotracheal tube. The remaining animal was anesthetized with intravenous pentobarbital, 30 mg./Kg.

The stimulating electrodes consisted of 2 copper plates, 4 by 6 inches, strapped on each side of the thorax in such a position that the cephalad edge of each electrode was approximately 4 cm. below the suprasternal notch, and the medial edge approximately 2 cm. from the ventral midline. Commercial electrocardiograph electrode paste was applied to the skin before placing the electrodes to ensure good electric contact.

Stimuli were given at a preselected time in the heart cycle by means of a delay circuit which was triggered by the QRS complex of the electrocardiogram. Capacitors of 25 or 50 μfd. were charged to the desired voltage, disconnected from the voltage source, and then discharged through the electrodes and the dog. Records of the stimulus current showed a single spike with exponential decay and no oscillations. The time constant of the exponential decay ranged from 1.1 to 2.7 msec. in different experiments, depending on the capacitance used and the resistance of the tissues between the electrodes. This resistance ranged from 37 to 55 ohms. The electrocardiogram (lead II or III) and femoral arterial blood pressure (Statham P-23A strain gage, Sanborn strain gage amplifier) were monitored throughout the experiment on a cathode-ray oscilloscope and a direct-writing recorder.

A total of 129 individual capacitor-discharge stimuli were studied. Each animal received from 4 to 30 stimuli, at intervals of not less than 5 min. in most instances. If the stimulus resulted in a conduction disturbance or arrhythmia, no further stimuli were applied until the electrocardiogram returned to normal, and an additional recovery period of approximately 10 min. had elapsed. When ventricular fibrillation was produced, a counter-shock of 440 V., 60 c.p.s. alternating current was applied through the stimulating electrodes, after the fibrillation had continued for at least 60 sec.

To produce the multiple extrasystoles and ventricular fibrillation being studied it was necessary to use peak voltages considerably above the range usually employed in physiologic experiments. The stimulus duration was relatively short, however, and no heating of electrodes or tissues was noted, even by direct measurements with thermocouples inserted under the skin and electrodes. Each

shock was accompanied by a single, brief, general-
ized contraction of the skeletal muscles. The skin
underlying the electrodes showed no damage after
repeated shocks. Eighteen of the 21 dogs sur-
vived the acute experiments and were observed for
1 week to several months, with no clinical evi-
dence of damage to the central nervous system
or other organs. Three dogs died in the course of
the experiments from ventricular fibrillation or
from cardiac arrest following defibrillation.

RESULTS

Preliminary tests showed that under these
experimental conditions the diastolic thres-
hold for single ventricular extrasystoles was
from 40 to 70 V. peak voltage, that no effect
except a single extrasystole occurred with
voltages less than 1.0 kv. and that ventricular
fibrillation was not observed with peak volt-
ages less than 2.5 kv. The experiments were
therefore designed to explore the range from
1.0 to 4.0 kv., with the results summarized in
figure 1. Results with 50 μfd. and 25 μfd.
capacitors are combined since there was no
apparent difference between them.

Single stimuli with peak voltages of 2.0 kv.
or more frequently produced a train of rapid
extrasystoles which appeared to be ventricular
in origin. This burst of ventricular tachy-
cardia was usually succeeded by a period of
complete atrioventricular block and ventricu-
lar standstill, followed by a period of partial
A-V block and then a gradual return to nor-
mal conduction and rhythm (fig. 2).

When the stimulus voltage was 2.7 kv. or
more the poststimulus tachycardia, instead of
slowing and being replaced by ventricular
standstill, sometimes accelerated and devel-
oped into ventricular fibrillation (fig. 3).
Ventricular fibrillation was produced 9 times:
twice by stimuli in the last third of systole,
corresponding approximately to the "vulner-
able period" which has been demonstrated
for the exposed or isolated heart[1,2]; 3 times
by stimuli earlier in systole, and 4 times by
stimuli during diastole.

Although no specific vulnerable period for
the production of either ventricular fibrilla-
tion or ventricular tachycardia and A-V block
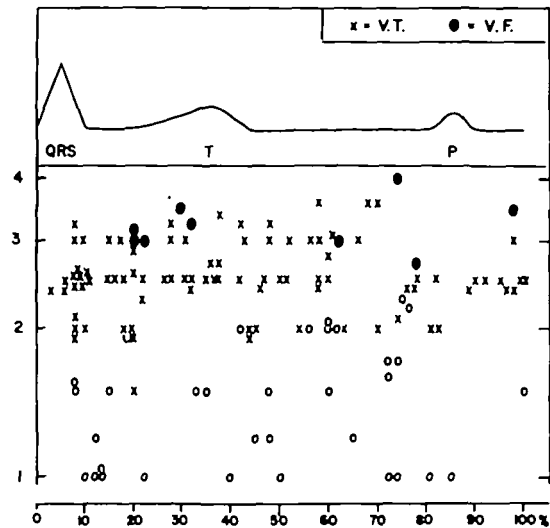could be demonstrated, an approximate volt-

FIG. 1. Results of 129 capacitor-discharge stimuli
in 21 dogs. *Ordinate,* peak capacitor voltage at dis-
charge, in kilovolts; *abscissa,* position of the stimulus
in the heart cycle, represents time interval from onset
of QRS complex to onset of stimulus expressed as
per cent of the total heart cycle, or R-R interval, of
the preceding beat. Each symbol represents one
stimulus and its effect. O, no effect except a single
extrasystole; X, multiple ventricular extrasystoles,
not followed by ventricular fibrillation; ●, ventricu-
lar fibrillation. The diagrammatic electrocardiogram
indicates the average QRS duration, Q-T interval,
and P-R interval in these experiments, in relation to
the total heart cycle.

age threshold for each effect is apparent in
figure 1. The threshold for ventricular fibril-
lation was in the neighborhood of 2.7 kv.; it
occurred with 26 per cent (9/35) of the stim-
uli from 2.7 to 4.0 kv., and not at all in the
94 trials with lower voltages. The threshold
for ventricular tachycardia and A-V block,
without fibrillation, was approximately 2.0
kv., since this effect followed 84 per cent of
the 99 shocks of 2000 V. and more, and only
13 per cent of the 30 shocks of lower voltage.
These thresholds were more clearly related to
peak voltage than to total energy of the stim-
ulus. The threshold of 2.0 kv. for multiple
extrasystoles, for example, is equivalent to 50
watt-sec. with 25 μfd., and 100 watt-sec. with
50 μfd.

From the blood pressure records it appears
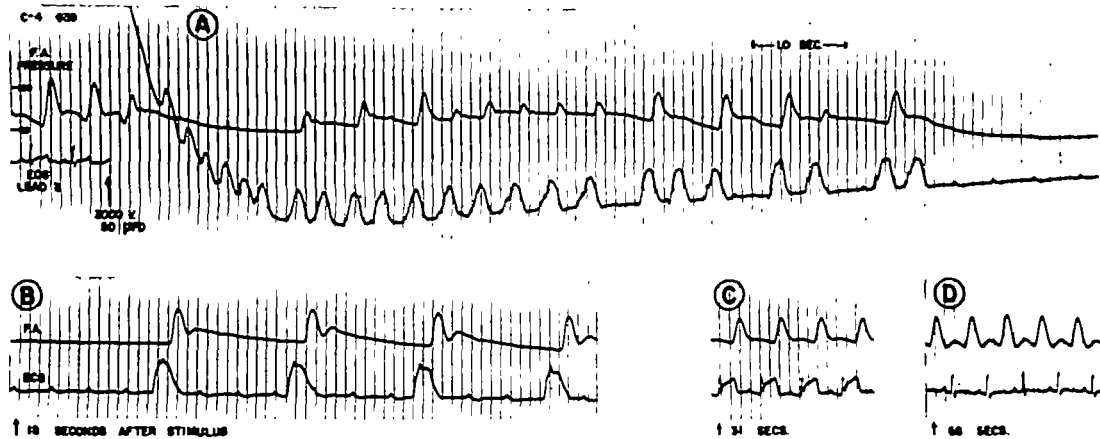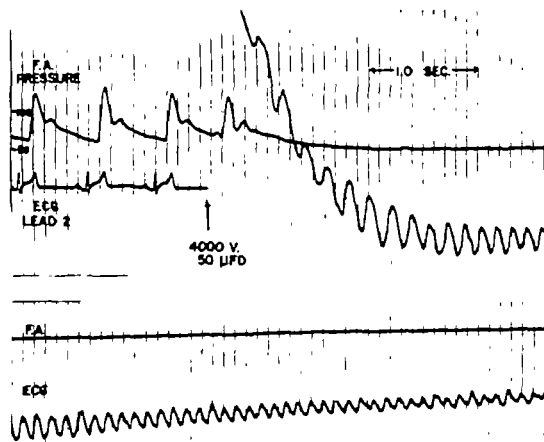that the first response to each stimulus was a

Fig. 3. Ventricular fibrillation produced by a single
stimulus (4000 V., 50 µfd.) applied in late diastole.
The two strips are a continuous record. The initial
response is a train of extrasystoles similar to those
in figure 2. In this instance, however, the rate of
the extrasystoles accelerates from approximately 330/
min. to 500/min., and the electrocardiogram takes
on the characteristic appearance of ventricular fibril-
lation. After 120 sec. of fibrillation, the arrhythmia
was terminated by countershock, but no spontaneous
pacemaker appeared, and the animal died in ven-
tricular standstill.

single ventricular extrasystole, which yielded
an arterial systolic pressure proportional to
the diastolic period preceding the stimulus.
The interval between the stimulus and the on-
set of pressure rise in the femoral artery for
this initial beat was approximately the same
(±15 per cent) as the interval from onset of
QRS complex to onset of arterial pressure rise
in the control period immediately preceding
the stimulus.

When multiple extrasystoles resulted from
the stimulus, the beats after the initial extra-
systole produced little or no arterial pulse
(fig. 2) either because the rapid rate (300 to
550/min.) did not permit sufficient diastolic
filling or because the mechanical response was
too weak to raise intraventricular pressure
and open the aortic valve.

Electrocardiographic records immediately
after the stimulus were distorted by a marked
displacement of the baseline (figs. 2 and 3).
It seems probable that this represents a large-
scale stimulus artifact attributable to the
capacitance-coupled amplifiers of our electro-

cardiograph, but we have not ruled out the possibility that it represents prolonged polarization of electrodes or tissues. It can be prevented by a current-limiting device in our recording apparatus if the peak stimulus voltage is less than 500 V., but we have not been successful in eliminating it with the voltages used in the present experiments. Although this displacement of the baseline obliterates the initial electrocardiographic response, as well as can be determined the subsequent ventricular beats arise from a single ectopic focus.

Complete atrioventricular dissociation was probably present immediately after the stimulus whenever multiple extrasystoles were produced, since P waves unrelated to (and usually at a slower rate than) the ventricular complexes could be seen in most cases. When ventricular fibrillation did not develop, the complete heart block persisted until the ectopic ventricular beats had slowed and stopped, and was followed by gradually decreasing degrees of partial A-V block. When A-V conduction returned to normal, intraventricular conduction disturbances often persisted for several minutes. These effects on conduction are similar to those of strong vagal stimulation, and the influence of vagolytic agents is being investigated.

Discussion

Vulnerable Period. One conclusion suggested by these results is that the boundaries of the "vulnerable period" for multiple extrasystoles and ventricular fibrillation depend in part on the parameters of the testing stimulus, at least under these experimental conditions. This has already been shown in the case of the absolutely refractory period for both nerve[5] and heart muscle.[6] In discussions of vulnerability or refractoriness, it has long been recognized that it is important to distinguish between a state of complete readiness to respond to a stimulus, and a state of partial readiness which may permit the receiving of a signal but does not permit response to it until after a specific latent period.[7] Moe,

Harris and Wiggers[8] showed that a single stimulus outside the vulnerable period can lead to ventricular extrasystoles and fibrillation, but only after a latent period extending to the end of the relatively refractory period. They presented evidence that their stimuli produced a prolonged local depolarization, and that it was the persistence of this depolarization into the vulnerable period that produced extrasystoles and ventricular fibrillation. In contrast to our results, they found that diastolic stimuli did not lead to ventricular fibrillation.

We can not rule out the possibility that a similar explanation applies to the present experiments. The displacement of the electrocardiogram baseline could be a manifestation of prolonged tissue depolarization, although the diffuse distribution of the stimulus current through the heart which results from large body-surface electrodes makes it unlikely that a sharply localized area of myocardial depolarization is produced.

In our opinion, however, the evidence from the arterial pressure records, showing that the interval between stimulus and initial response is constant, and of the same magnitude as the normal electric-mechanical delay, suggests that prolonged depolarization is not the operative mechanism here. The interval between stimulus and initial response was the same whether ventricular fibrillation or only a single extrasystole was produced, indicating that the first extrasystole resulted directly from the stimulus. If prolonged polarization lasting into a limited late-systolic vulnerable period were the agent responsible for fibrillation, it would have to act during recovery from this first beat, and the *second* poststimulus beat should occur earlier than was observed in these experiments.

Initiation of Fibrillation. The first response in the chain of events which leads to ventricular fibrillation in these experiments, as in those of Moe, Harris and Wiggers,[8] is a ventricular extrasystole, seemingly no different from the single extrasystoles elicited by stimuli of lower voltage. This beat initiates a se-

ries of rapid ventricular extrasystoles which either accelerate (Wiggers'[9] "tachysystolic phase") and become ventricular fibrillation, or slow gradually and cease. This sequence of events fits the hypothesis[9] that an ectopic focus is created which is responsible for the few extrasystoles, and that ventricular fibrillation results if these extrasystoles occur at a sufficiently rapid rate in an environment which encourages re-entry. We are at a loss, however, to explain the difference between the instances in which ventricular fibrillation occurs and those in which it does not, or to explain why a voltage threshold exists for these effects. Repetitive firing in nerve in response to direct current stimuli[10, 11] is probably an analogous phenomenon. Rosenblueth's observation that the number and frequency of repetitive pulses is directly proportional to the stimulus intensity[11] suggests a relationship with the present observations.

Whatever the mechanism involved, we can conclude that the concept of a "vulnerable period" limited to a relatively short part of late systole does not apply under all conditions to the intact animal. If we define the "effective vulnerable period" as that period during which a single stimulus can bring about ventricular fibrillation without regard to latency between stimulus and response, then this period extends throughout most of the heart cycle for the stimuli used in these experiments.

SUMMARY

Experiments were carried out on 21 anesthetized dogs to determine vulnerability to ventricular fibrillation from single stimuli consisting of capacitor discharges through external electrodes on the thorax. Capacitors of 25 to 50 µfd. charged to voltages of 1.0 to 4.0 kv. were used. Voltages from 2.0 to 4.0 kv. produced multiple ventricular extrasystoles and atrioventricular block, usually followed by transient ventricular standstill and gradual return to normal rhythm. In 9 of 35 tests with peak voltages of 2.7 to 4.0 kv., the multiple ventricular extrasystoles developed into established ventricular fibrillation.

Susceptibility to these effects extended throughout most of the heart cycle and was not limited to the relatively short late systolic "vulnerable period" observed in the exposed heart.

SUMMARIO IN INTERLINGUA

Esseva executate experimentos in 21 canes anesthesiate pro determinar lor susceptibilitate al disveloppamento de fibrillation ventricular como responsa al singule stimulo de un discarga de condensator via electrodes externe applicate al thorace. Esseva usate condensatores de inter 25 e 50 µfd, cargate a voltages de 1,0 a 4,0 kv. Voltages de 2,0 a 4,0 kv produceva multiple extrasystoles ventricular e bloco atrioventricular, sequite usualmente per un transiente arresto ventricular e le retorno gradual a un rhythmo normal. In 9 ex 35 experimentos con voltages maximal de 2,7 a 4,0 kv, le multiple extrasystoles ventricular se disveloppava in establite fibrillation ventricular.

Susceptibilitate a iste effectos esseva notate in quasi omne phases del cyclo cardiac. Illo non esseva limitate al relativemente breve termino-systolic "periodo de vulnerabilitate" que es observate in experimentos con le corde exponite.

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