dangerous defects of an artificial cardiac pacemaker.

The rate thresholds for various abnormalities differed enormously from animal to animal but remained relatively constant in the same heart. Since there was considerable overlap in frequency ranges, the averages obtained were merely approximations of the rates at which particular types of abnormality might be expected. Calculations of deviations from the mean were no more helpful.

Summary. Hearts of anesthetized dogs were driven at slowly accelerating rates from atrial or ventricular electrodes. The rate thresholds for various abnormalities and failures were determined for both types of drive. Pulsus alternans occurs at a slower rate during atrial than during direct ventricular drive. Conduction from ventricle to atrium fails at slower rates than does A-V conduction. Alternation in electrical response voltage and ultimately 2:1 stimulus-electrical response ratios develop at high rates of drive in both atrium and ventricle much more commonly than do fibrillation or other irregularities of response. Sudden changes in rate and irregularities of stimulus pulse spacing are more apt to disorganize cardiac function than are progressive rate changes.

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Excitable Cycle of the Heart as Determined by Mechanical Stimuli.* (29656)

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The excitable cycle of the heart has been defined almost entirely by electrical stimulus testing. This method has shown that absolute and relative refractory periods are followed by a phase of supernormality(1). Within the terminal portion of the relative refractory period there is also a phase of relative supernormality to anodal current. This was referred to originally as a "dip" in the excitability recovery curve(2). During this "dip" phase the myocardium is also vulnerable to fibrillation by supra-threshold electrical pulses(3) and this concept of a vulnerable period in the excitability cycle is generally accepted. The question rises as to whether this is a specific vulnerability to electrical shock only or to all types of stimulation as well.

The period of refractoriness is possibly more correctly spoken of as an unresponsive period since stimuli applied during the relative refractory phase do evoke a response

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eventually. Latency increases as stimuli are placed earlier and earlier as though a time-requirement-for-recovery, specifically related to heart rate, prevents an earlier beginning of a propagated response(1). Changes in latency of responses as well as changes in excitability threshold serve to identify recovery of normal membrane state following excitation.

It is well known to any one who has worked with a living heart that touch or pressure can initiate a response which originates at the site of this contact. Single or multiple mechanical stimuli can also cause fibrillation at least under somewhat abnormal conditions. Studies of the effects of stretch or distention on mechanical reactions(4) and on heart rate (5) have been quite numerous but there have been very few tests of the effects of mechanical stimulation or of changing thresholds to mechanical stimuli during the cardiac cycle. The purpose of the present work was to compare cardiac responses to electrical and mechanical stimuli.

Methods. The responsiveness of the ventricles of dogs anesthetized with nembutal (30 mg/kg) was tested throughout the cardiac cycle by application of quick transient mechanical stimuli. The heart was exposed by a mid thoracic incision and supported in a pericardial cradle. Artificial respiration was given and by stabilizing the chest movement of the heart associated with respiration was prevented. Nevertheless, the cyclic changes in heart volume caused changes in rigidity of ventricular walls and in the distance of surfaces from the stimulating rod.

Hearts were driven at a fixed rate through atrial driving electrodes. In most cases the sinoatrial node was crushed to permit slower rates of drive and longer cycles. Driving stimuli maintained a cycle length of 600 or 500 msec simultaneously triggering an oscilloscope sweep in which were recorded surface electrograms or ventricular monophasic action potentials. Stimulating and recording electrodes were attached to the surfaces of both ventricles by superficial stitches. The monophasic action potentials were obtained by applying 25 lb of suction through a 1.5 mm diameter orifice in a 6 by 12 mm rectangular plastic block resting on the heart surface. The tip of a small silver wire made contact with the injured tissue while another lead also embedded in the block made contact with uninjured tissue 3 to 5 mm from the suction orifice. These leads were connected to appropriate amplifier and recording circuits(6).

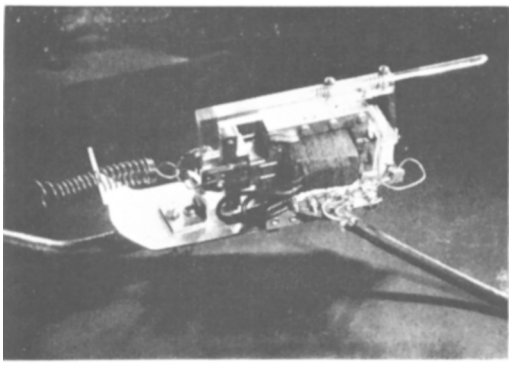
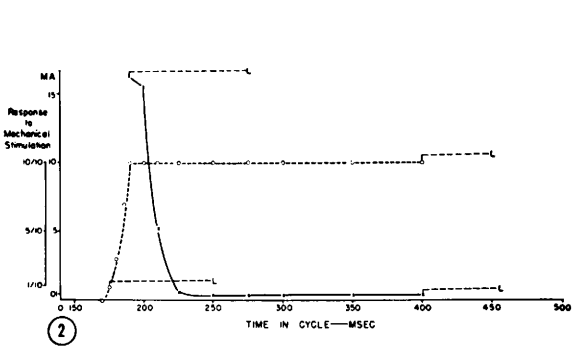


FIG. 1. Mechanical stimulator showing stimulating rod, the solenoid assembly and return spring.

Rectangular pulses 1 msec in duration and of controllable amperage applied through surface electrodes were used to quantitate changes in electrical excitability. Mechanical stimulation was effected by a thrust from a plastic rod 4 mm in diameter, tapered to a 1 mm rounded tip (Figure 1). In order to obtain a thrust and withdrawal of fixed speed and distance this rod was attached to the moving core of a solenoid. Switch contacts were so arranged that the mechanical stimulus (rod thrust) could, like the electrical testing stimuli, be delivered at any desired interval of the cycle. The tip of the rod was positioned 1 cm above the heart surface and a 1.2 cm thrust delivered during an interval of 70 msec. The force was constant and the deformation of or contact with the heart muscle must have lasted approximately 10 msec. Because of changes in heart diameter and consequent changes in closeness of rod tip to muscle surface the period of stimulating deformation may have varied between 10 and 20 msec but never exceeded 30 msec. These stimuli were, however, relatively constant for any period of the cycle. An attached circuit signalled tip contact with the heart



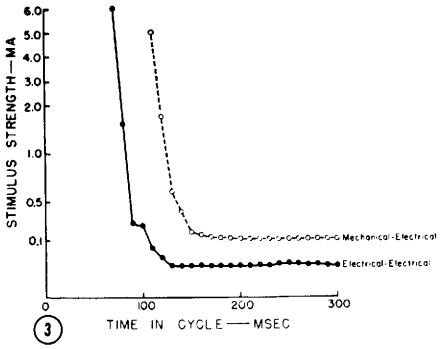


FIG. 2. Graph of electrical (solid line) and mechanical (broken line) stimulation of ventricle. Dashed lines show latency of diastolic and earliest responses evoked in cycle-beginning of line at time of stimulus and L shows time of response. Change in excitability shown for both stimuli. Scale at left shows mechanical stimulus-response ratios as this changes for mechanical stimulation during relative refractory period.

FIG. 3. Comparison of excitability recovery curves of electrical and mechanical stimulation (see text).

and an artifact showed in the oscilloscope trace permitting measurement of response latency.

The degree of thrust thus produced invariably excited the ventricle during diastole. Mechanical stimuli, like electrical, were delivered only every 8 to 12 cycles. When testing comparative latencies of response, electrical and mechanical stimuli were applied at equal distances from recording electrodes and the on-off stimulus artifacts were recorded on the sweep monitoring the propagated action potentials.

Results. The biphasic and monophasic action potentials initiated by electrical and mechanical stimuli showed no significant differences. Latencies of response to the two types of stimuli, as calculated from responses under pick-up electrodes, some one or one and a half centimeter distant from point of stimulation, were also practically the same. Also, there was no difference between the 2 ventricles in "thresholds" to electrical and mechanical stimuli or in durations of their unresponsive periods.

Thresholds to electrical stimulation could readily be determined by changing strengths of stimuli. There was no means of doing this in the case of mechanical stimuli, but a fact was observed which permitted some estimation of a relative refractoriness. During diastole every mechanical blow produced a response of uniform latency. As the mechanical stimuli fell earlier and earlier, a point in the cycle was reached at which responses occurred only after each second or third thrust delivered at this period. When a response did originate, it had a longer latency. Fig. 2 shows how, in the case of both electrical and mechanical stimulation, changes in latency identify borders of the unresponsive and relative unresponsive period. It also shows how, by calculating changes in ratio between thrusts (mechanical stimuli) applied and responses evoked, a definition of the relative refractory period can be derived which is consistent with the definition as given by electrical stimulus testing.

Fig. 3 shows how the excitability recovery curves, obtained by electrical and mechanical impulse testing, agree. The fact that the mechanical stimulus curve is placed above the electrical has no significance since rate, extent and duration of deformation cannot be compared with voltage or amperage or electrical stimuli. It is more significant that neither supernormality, a dip, nor a phase of vulnerability was identifiable by mechanical stimulation.

Discussion. It was anticipated that mechanical stimulation would quickly injure the heart muscle and that it would readily produce repetitive extrasystoles and fibrillation. It was found that at testing rates of one thrust per 12 beats a point would retain its excitability, responding to each stimulus for

hours. Also, no phase of the cycle was found during which a single mechanical stimulus would invariably produce either repetitive firing or fibrillation. To produce fibrillation with any predictability, thrusts at a high rate (during each cycle) for a number of beats (20 to 40 cycles) were required. Stimuli applied over the septum between the 2 ventricles appeared to be more effective but often it was not possible to induce fibrillation without creating obvious injury. Fibrillation by mechanical stimulation might be much easier under conditions such as hypothermia when power of accommodation is reduced(7,8).

These results indicate that depolarization by electrical and mechanical means have about the same end result. During the late phases of repolarization and recovery of the membrane, mechanical as well as electrical stimuli can depolarize or excite again. Supernormality cannot be detected by means of mechanical stimulation. The absence of vulnerability supports the concept that this is a phenomenon of anodal repolarization(1,9).

The fact that repetitive mechanical stimuli appear to have a summating effect during the relative refractory period is difficult to explain other than on the basis of a chemicophysical change which might be called slight injury. This and the change in latency of response does indicate a recovery process. There does appear to be a period of absolute unresponsiveness to mechanical stimulation.

Summary. The excitability cycle of the heart was studied by means of mechanical stimulation. Absolute and relative refractory and unresponsive periods were found which compared well with identifications made in the same hearts by electrical stimulation. No supernormal periods or vulnerable periods were found when mechanical stimuli were used.

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