Experimental and laboratory reports

Physical principles of artificial stimulation of the heart. Stimulation of the canine heart in situ

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There are many methods of stimulation of the heart in case of cardiac arrest. To define our subject, we believe it is sufficient to mention the principal methods: (1) Stimulation of the heart by means of electrodes placed externally on the chest.[1] This method is very painful to the patient because of contraction of the skeletal muscles and irritation of the skin under the electrodes. (2) Direct stimulation of the heart by means of electrodes placed near or on the heart.[2] In this case the electrodes can be connected with a stimulator placed externally or in the patient's abdominal wall. (3) Stimulation of the heart by means of an electrode mounted on the tip of a catheter that is placed in the right ventricle, with the other electrode in a thoracic subcutaneous position.[3] The stimulator is in an external position. This is the method used in our experiments. (4) Stimulation from a source that is located in an external position on the chest and connected inductively with an opposed coil which, with a rectifier, is sutured subcutaneously and connected by means of platinum wires to the myocardium.[4] The advantage of this method is that quantities such as frequency rate and current curve amplitude, in milliamperes, can be controlled and tested; this, of course, also applies to the first three methods mentioned.

The life of the batteries, infections, and mechanical defects still play a role of importance in these methods, so that further investigation and improvement are necessary. Artificial stimulation of the heart, however, has yielded methods entirely practicable from the point of view of physics,

Nevertheless, it must be borne in mind that a feature which is common to all these methods is their serious effect on the patient.

Some physical principles

A critical analysis of heart stimulation may be useful, because there are indications of a degree of misapprehension in regard to the physical quantities involved in stimulation.

a. The passage of a current through the organism is associated with ion transport. Certain membranes in the body, when in the resting state, are passed more readily by K than by Na. At the passage of a current, a change in ion concentration can occur on one side of a membrane, and this may give rise to a physiologic action, such as muscle contraction. It can be maintained in general that, in the case of a direct current, the physiologic influence is dependent on the local density of current $\vec{j}$, which is defined as the charge passing, per unit of time, through a surface area

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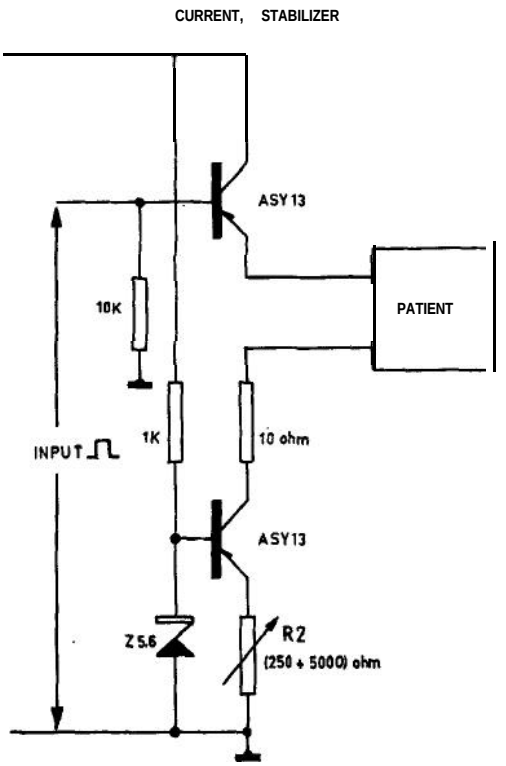

Fig. 1. Current stabilization circuit with the patient in the circuit.

of 1 square centimeter perpendicular to the lines of flow, and on the duration τ of the current passage.

Under a given intensity of current between the electrodes, even if its duration is unlimited, no reaction occurs (rheobase). Of course, the intensity of current during the time should be reproducible and controllable, that is, it should not depend on various impedance variations in the tissue.

It is clear that, for the purpose of heart stimulation, a reproducible stabilized intensity of current between the electrodes should be applied during a time of the order of magnitude of a time characteristic of the heart, e.g., chronaxy. Rheobase and chronaxy of the myocardium will be discussed later. With a view to the spatial problems encountered in heart stimulation, the density of intramyocardial current is the essential physical quantity *(not,* as is often indicated in various publications and on instruments, the height of the pulse in "volts"). The latter may have dangerous consequences for the patient and must be rejected,

b. Obviously, stabilization of current is required in order to prevent distortion of the current curve in the tissue. Therefore, the internal resistance of the pacemaker must be high relative to the patient's impedance and variations in impedance. The internal resistance of the pacemaker can be made high, say, by including in the patient's circuit a series resistance, which is very high relative to the patient's variations in impedance. This, however, is an energy-consuming method.

A high, effective, dynamic R_i can be ensured by the transistor circuit shown in Fig. 1. As an example, it can be stated that, at a rectangular current pulse amplitude of 10 mA., and with a patient's resistance varying from 100 Ω to 1 k Ω, the R_i of this current amounts to 2 X 10^5 Ω. The amplitude can be regulated by means of potentiometer R_2. A current curve with an

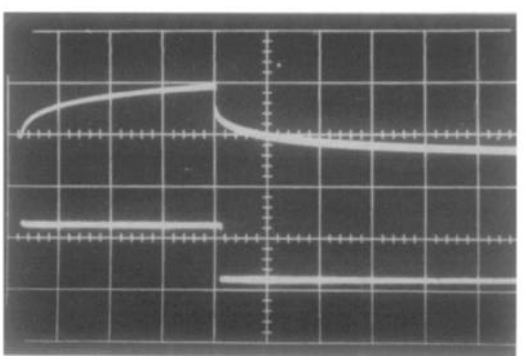

Fig. 2. *Upper* curve: Voltage with sensitivity 1 V./cm. *Lower* curve: Current with sensitivity 10 mA./cm. Time scale : 1 msec./cm. With current stabilization.

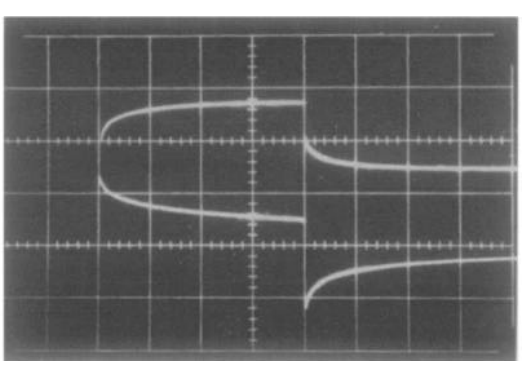

Fig. 3. Upper *curve:* Voltage with sensitivity 1 V./cm. *Lower curve:* Current with sensitivity 10 mA./cm. Time scale : 1 msec./cm. Without current stabilization.

amplitude of 20 mA. is stabilized for 100 per cent at a load of 1 k Ω. This circuit, therefore, affords a high degree of stabilization to prevent distortion of current configuration. The direct voltage used to supply the transistors is 28 volts. Of course, there are other arrangements to produce a high source impedance.

Fig. 2 shows a photographic record with the patient in the circuit, with application of current stabilization. The current curve configuration is indeed rectangular.

Fig. 3 shows the distortion of the current curve with the patient in the circuit when no current stabilization is applied. Here, the current pulse had become a sport of the processes in the tissues. There is no longer any question of a reproducible charge per rectangular pulse.

The intensity of current of every pacemaker can be studied as a function of load impedance.

Fig. 4 shows such a relation plotted for a commercial pacemaker with, as parameter, the intensity of current in milliamperes at 100 Ω. The stabilization of current is seen to he insufficient at greater load impedance.

c. As we pointed out, the method of Furman and Schwedel[3] was used in our experiments and applications. By electronic means the relation between current and voltage can be made visible on the screen of a cathode-ray oscillograph while the patient is in the circuit. The quotient indicates the resistance (Ohm's law). When this method is used, the patient's resistance, measured between the electrodes is found to fluctuate between 100 and 200 Ω. With the implantable method of stimulation the initial resistance is 400 Ω, and in some cases this increases within a few months to a few k Ω's. This confirms the importance of stabilization of current.

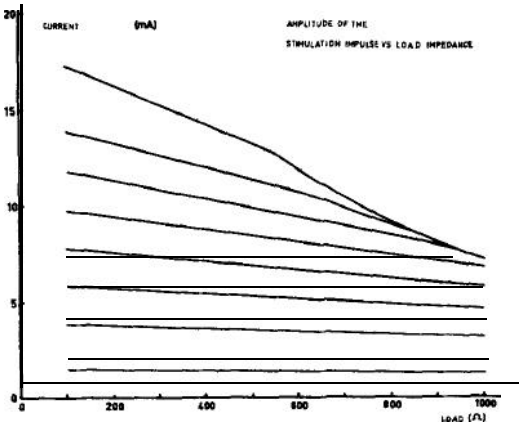

Fig. 4. Current intensity in milliamperes as a function of the load impedance.

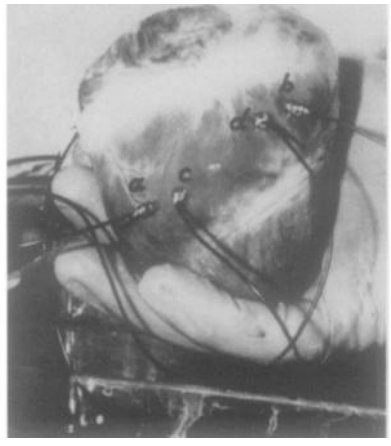

Fig. 5. Electrodes *a* and *b* are suppliers of current. Electrodes c and dare voltage electrodes.

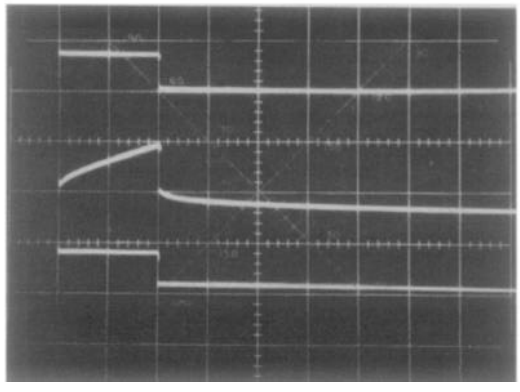

Fig. 6. Upper *curve:* Voltage measured between electrodes *a* and d. *Middle* curve: Voltage measured between electrodes a and *b*. *Lower curve:* Current measured between electrodes a and *b*. Sensitivity *0.2* V./cm. Time scale: 1 msec./cm.

It is clear that the initial resistance in the implantable method must exceed that in the Furman catheter method, in view of the fact that the resistance "of" a spherical electrode placed in an electrolyte or in tissue is given by-the equation

$$R = \frac{\rho}{4 \pi r},$$

in which R = the resistance "of" a spherical

electrode placed in electrolyte or tissue, ρ_1 = the specific resistance of electrolyte or tissue, and r_1 = the radius of the electrode.

When an electrode is placed in electrolyte or tissue, the resistance is determined chiefly by the radius r of the electrode. The maximum resistance is near the electrode, and it is inversely proportional to the electrode radius; this explains the high initial resistance with the implantable method on the basis of the small r. Moreover, ρ tissue $\simeq$ 350 Ω cm. > ρ blood $\simeq$ 145 Ω cm.

d. It is worth while to note that a polarization effect on voltage occurs near the electrodes. To demonstrate this, we used the so-called four-electrode method in our experiments. As Fig. 5 indicates, four electrodes of V2A steel were inserted. Electrodes a and *b* are the suppliers of current; voltage is measured between electrodes *c* and d. The electrodes have a diameter of 1 mm. The voltage measured over *c* and *d* can be compared with the voltage measured between a and *b*. The experimental arrangement is shown in Fig. 5. The measurements were made on the right ventricle of the porcine heart, postmortem.

The results of the measurements, photographed from the oscillograph screen, are shown in Fig. 6. The middle voltage curve was measured over a and *b*, simultaneously with the lower (current) curve, which has been stabilized. The voltage curve clearly demonstrates the influence of the polarization of the electrodes.

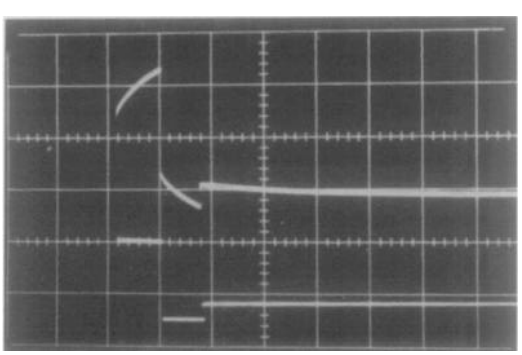

Fig. 7. Diphasic stabilized current curve. *Upper* curve: Voltage with sensitivity 0.2 V./cm. *Lower* curve: Current with sensitivity 5 mA./cm. Time scale: 1 msec./cm.

e. When a direct current passes through an electrolyte, substances are deposited on the electrodes. Faraday's law states that the quantity of substance deposited is exclusively dependent on the intensity of current, the time, and the nature of the substance. In artificial heart stimulation, we are also dealing with electrolysis. To date, little information is available in regard to the influence which electrolysis at the electrodes exerts on the tissue. Work on this subject has been done by Dittmar,[9] who studied the nature of the electrode

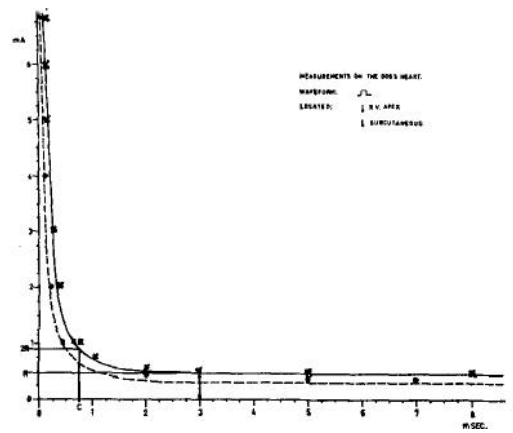

Fig. 8. Response of the canine heart with block to variations in curve duration and amplitude. Frequency rate: 110 per minute. Position of electrodes: Inside right ventricular apex and subcutaneously in the thorax.

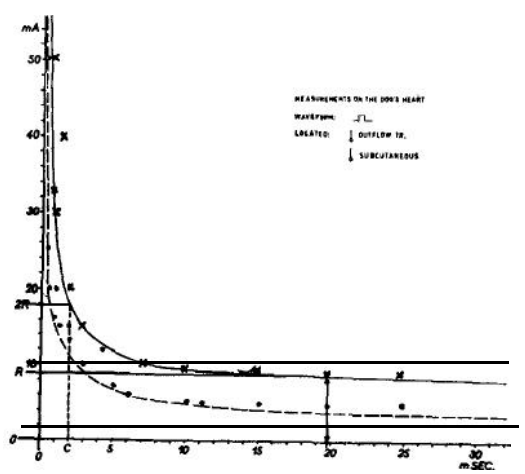

Fig. 9. Response of the canine heart with block upon variation of current curve duration and amplitude. Frequency rate: 110 per minute. Position of electrodes: Outflow tract of right ventricle and subcutaneously in the thorax.

material in relation to its influence on adjacent tissue.

The question now arises whether the use of a diphasic current pulse would not be advisable. We did some experiments with the current curve shown in Fig. 7. The zero level of the curve is adjustable throughout the curve's amplitude. The diphasic current curve can be varied in duration, amplitude, and frequency rate, and, of course, has been stabilized. But a choice such as that shown in Fig. 7 virtually lacks compensation of polarization.

The experiments were carried out on canine and calf hearts in situ.

As a result of our observations, we can say that the heart in all cases showed a strong tendency to fibrillate; further investigation into the configuration of this curve is, therefore, desirable.

f. The hemodynamic consequences of stimulation open further avenues of investigation. The mode of contraction of the heart under the influence of a rectangular current pulse with adjustable duration and amplitude should be studied. The movements of the cardiac wall should be studied with the aid of electrokymograms. A study of the stroke volume of the heart could be made with the aid of an ultralow-frequency ballistocardiograph or by the dye injection method.

Stimulation of the canine heart in situ with block

At this time, the question of why the heart contracts under the influence of a rectangular current pulse of given amplitude and duration cannot yet be answered. Experiments on the canine heart in situ with block, however, can teach us how contraction or noncontraction depends on current i and duration τ. For our experiments, A-V block was produced in a canine heart in the manner described by Meyler and associates.[6]

In our experiments we have attempted to answer the question whether it is possible to obtain a chronaxy-rheobase diagram of the heart. For this purpose an electronic unit was designed which is capable of supplying stabilized current pulses of rectangular configuration and adjustable amplitude, duration, and frequency rate.

The duration of the current pulse can be varied from 20 μsec to 1 second. Its amplitude can be varied from 20 μA to 100 mA. The frequency rate can be varied from 30 to 180 pulses per minute.

With a spherical electrode of V2A steel (ϕ 2 mm.) on the tip of a catheter in the apex of the right ventricle (− electrode) and another spherical electrode (ϕ 2 mm.) placed subcutaneously in the thorax, experiments with varying pulse duration and amplitude yielded the result recorded in Fig. 8.

The measuring points marked (x) indicate that the heart followed completely, whereas the measuring points marked (•) indicate that the heart followed partly, the imposed frequency rate.

With one electrode in the outflow tract of the right ventricle and the other implanted subcutaneously in the thorax, we obtained the result shown in Fig. 9.

The measurements warrant *the following conclusions:*

1. The values of chronaxy and rheobase are largely determined by the position of the electrode in the right ventricle. With the electrode in the outflow tract, the chronaxy was 2 msec. It was 0.8 msec. when the electrode was situated in the apex of the right ventricle. Fig. 8 shows that the rheobase was 0.5 mA. with the electrode in the apex of the right ventricle; in the other location (Fig. 9) the rheobase

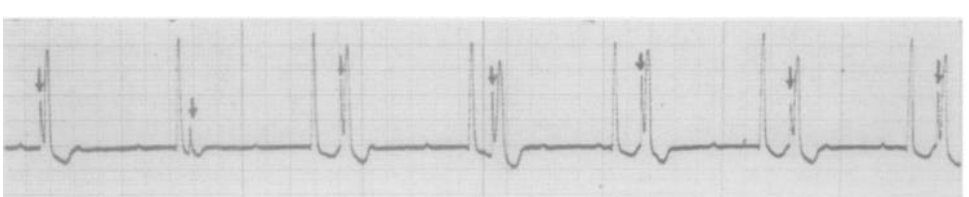

Fig. 10. Partial following of the imposed frequency rate in a canine heart with block in situ. Paper speed of 25 mm. per second. Lead Vs.

was 9 mA. It is clear that the rheobase is a function of the electrode position. The measurements were repeated in 3 different dogs with heart block, and results were found to be reproducible with a 5 per cent variation.

2. Changes in the position of the thoracic electrode within a radius of 15 cm. proved to exert no influence on the results of measurement.

3. Above and to the right of the drawn curve (Figs. 8 and 9), the heart completely followed the imposed frequency rate. The form of the drawn curve is:

$$i = \frac{a}{t} + b,$$

in which i is the intensity of current in milliamperes, and t is the duration of the current curve in milliseconds, while a and b are constants. (This can be verified in the usual physical way by plotting $i \times t$ versus t.)

4. Between the continuous and the interrupted curves the heart partly follows the imposed frequency rate. In this respect, the phase which the heart is in when the current pulse begins plays a role. The heart is more sensitive to a stimulating impulse the longer ago was the previous spontaneous contraction. This can be demonstrated by triggering on the QR flank of the QRS complex in a dog with a normal cardiac rhythm or with heart block, and allowing a current pulse to arrive after an interval adjusted by electronic means.

Fig. 10 illustrates this. The peaks indicated by arrows represent the stimulating pulses.

We also observed a pronounced difference in QRS duration between the provoked beats and the spontaneous beats. The relation between chronaxy and rheobase, on the one hand, and phase, on the other, should be studied in more detail. Important work in this respect has been done by Van Dam and associates.7

Summary

1. In artificial heart stimulation, the essential quantity is the density of current, $\vec{j}$, in the intramyocardial wall. Dosage of the pulse amplitude in volts can have serious consequences for the patient. Curve indications in volts on pacemakers and in publications and records must, therefore, be rejected.

2. Hence, the pacemaker should supply stabilized current pulses even while the load impedance is increasing.

3. The distortion of the voltage curve at stabilized current is an electrode effect.

4. Separate measurement and registration of the physical quantities involved in stimulation is advisable. The values obtained in every individual patient warrant conclusions as to the method of choice. It is recommended that one start with the Furman and Schwedel method, i.e., with one electrode in the right ventricleand the other placed subcutaneously in the thorax (a noncritical location).

5. Measurements on the canine heart in situ with block, carried out with currents pulses of rectangular configuration, revealed that, when the Furman method is used, chronaxy and rheobase of the myocardium are dependent on the position of the electrodes.

6. The phase which the heart is in when the current pulse is supplied is a factor of importance for the heart's following of the imposed frequency rate.

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