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The nature of electric defibrillation of the heart

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Summary

It has been shown experimentally that electrical defibrillation of the heart is the result of synchronization of separate heart elements. Bipolar impulses have been found to be the most effective technique for defibrillation. It had the advantage that the excitatory effect was determined by the sum of the amplitude of both half-waves of the current, and the damaging effect was determined only by the value of the first half-wave. The decisive role of the steepness of the rear-front of the impulse on the effect of cardiac defibrillation is also shown.

Introduction

Excessive or protracted electrical defibrillation of the heart may also prove harmful, as well as having a therapeutic effect. Formerly, when defibrillation was considered to result in suppression of ectopic centres of automatism, the attendant disturbances of cardiac function like extrasystoles, disturbances in conduction or asystole were regarded as inevitable disadvantages. The injurious and therapeutic effects seemed to be connected, since both were due to suppression of cardiac function by strong current. Meanwhile the erroneous conception emerged that the stronger and more prolonged the current the more reliable was the defibrillation. Defibrillation by protracted application of alternating current, which injured the heart, was a graphic consequence of such thinking.

More recently, it has been established that electric defibrillation acts by synchronizing the excitation of all elements of the heart. Thus the prospect of minimizing the harmful effect of high current on the heart became real; the magnitude and duration of the current could be limited to the minimum required for defibrillation. This could produce a therapeutic effect without injuring the heart in any way. Thus the problem resolved itself into choosing an adequate form of electric impulse with the minimum strength and duration, which would defibrillate the heart. The prolonged use of alternating current became unnecessary since excitation of the heart could result from the action of a single impulse lasting a few milliseconds. On the other hand, the use of too short impulses as an aperiodic condenser discharge was also inexpedient because the very strong current necessary in this case might seriously injure the heart. The strength of the current of the discharge was reduced and its duration increased to the 'useful time' of 8–10 ms, taking into account the inductance in the discharge chain (Gurvich, 1957; Gurvich & Makarychev, 1967). Such discharge proved effective with the minimum current, and harmless to the functional activity of the heart. The advantages of the method suggested are now generally recognized, and application of a single impulse in the form of a condenser discharge through inductance is now accepted as standard.

Unfortunately, the specific conditions of electric defibrillation, namely, the penetration of a strong stimulus uniformly throughout the whole heart, requires extremely strong current (20–30 A), even with the most adequate form of impulse generated by the ID-66-T Soviet Defibrillator. The situation is even worse in this respect of the Defikard, Fibrillestop and other defibrillators, in which the inductance is either very low or totally absent; with an energy of discharge amounting to 400 J (which passes completely through the patient with such apparatus), the current reaches such extremely high values as 75–100 A, which may seriously damage the heart.

The necessity of reducing the strength of the defibrillating current is dictated by the extensive use of defibrillators for resuscitation, as well as the treatment of chronic arrhythmias. The necessity to defibrillate the same patient more than once in acute diseases of the heart, like myocardial infarction, requires the optimum qualities of the defibrillating impulse. In such cases, even a slight reduction in the current may play a decisive role in the final success of the treatment, and in saving the patient's life.

Bipolar impulses for stimulation

We found it possible to enhance the effectiveness of the stimulus and reduce the defibrillating current used by employing bipolar impulses, a fundamentally new method of stimulation. By this means the heart may be excited by the near-front wave (disappearance of the anelectrotonus), whose amplitude may be double the fore-front by changing the direction of the current without increasing its strength. Owing to this peculiarity of the bipolar impulse, defibrillation may result from the composite action of both half-waves of the impulse.

This supposition was substantiated by an earlier study of the magnitude of injuries resulting from alternating and direct currents. Experiments have shown that rectifying an alternating current into pulsating current doubles the threshold value of the current causing cardiac fibrillation. The results of these experiments were explained by the fact that the excitable tissue of the heart reacts to the entire flow of increasing or decreasing current, i.e. to the total oscillation of alternating current (peak to peak) without perceiving the change in the direction of the current.

We have studied the effect of summation of the stimuli of both half-waves of alternating current on defibrillation of the heart (Gurvich & Makarychev, 1967; Gurvich, Tabak, Bogushevich, Venin & Makarychev, 1971). Twice the current of rectified pulsating current was needed to defibrillate the heart with the threshold value compared with the use of alternating current before rectification. The effect of summation of the stimulatory action of the two half-waves was also observed equally for the bipolar discharge. Stopping the current during the second half-wave necessitated an increase in the current of the first half-wave to the total value of the amplitudes of both half-waves in order to reach the threshold of defibrillation. Thus it was concluded that with an equal amplitude of current in both half-waves, the bipolar impulse was capable of defibrillating the heart with less current than was necessary for the monophasic impulse.

Initially the apparatus was designed to generate an impulse with an equal amplitude of current in both half-waves by discharging a capacity of 16 μF through an inductance of 0·1 H with a 40 ohm output shunt and a diode in the circuit. However, this apparatus failed to produce the total summation of the stimulatory action of both half-waves. Instead of the intended 50% decrease in the current of each half-wave compared with the debribrillating current of the monophasic impulse, only a 25% decrease was observed, and the total current of both amplitudes thus exceeded the amplitude of the monophasic impulse by 50%. Photography of the traces indicated that the cause of the low effectiveness of the impulse was due to distortion of its form; in the rear-front wave there was an insignificant break. Unlike the first half-wave, which was sinusoidal, the second half-wave resembled an aperiodic discharge. Apparently the brief distorted first half-wave, lasting less than 5 ms, failed to polarize the tissue under the anode sufficiently to stimulate the heart during the change in the direction of the current. We therefore increased the current of the first half-wave compared with that of the second half-wave.

The connection between the summation with insufficient duration of the first half-wave and the distortion of its rear-front was confirmed. The impulse became much more effective when a regular sinusoidal impulse was used. This was accomplished by an increase in the resistance of the output shunt to 80 ohms, the ratio of the half-waves thereby decreasing to 1 : 0·65–1 : 0·7. Under these conditions a total summation of both half-waves of the impulse was observed (Gurvich *et al.*, 1971), although the amplitude of the current of the first half-wave constituted only 60% of the amplitude of the defibrillation current with the monopolar impulse (Fig. 1).

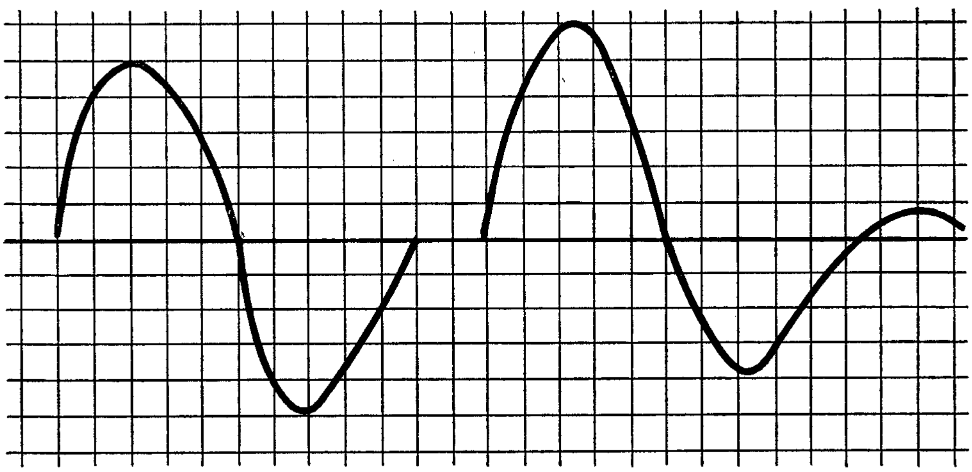

Fig. 1. Oscillograms of diphasic pulses: left, ineffective form of impulse (the effect of both half-waves is not summated); right, effective form. Each square is 5 A vertically, and 2 ms horizontally.

The dependence of summation of the stimulatory action of both half-waves of the impulse on its form which we had found was of some interest because it indicated a special significance of the gradient of the rear-front of the impulse on its effectiveness. A similar conclusion may be drawn from the analysis of other phenomena of cardiac defibrillation. These include the reduced effectiveness of triangular pulses and aperiodic discharges when their duration is increased beyond certain limits (Geddes, Tucker, Macfarlane & Bourland, 1970; Schuder, Stoeckle & Rahmoller, 1966). The increase in defibrillating current with an increase in the duration of the stimulation beyond a certain limit is not explained by the classical ideas on parameters of electric stimulation, but is apparently a peculiarity of electric defibrillation of the heart.

Our studies of the particular properties of cardiac defibrillation with protracted pulses (up to 30 ms and longer at the isoelectric line) have shown that the degree of increase in the threshold of defibrillating current with protracted impulses is determined by the gradient of the rear-front (Fig. 2). Changes in the fore-front of the impulse from steep (with discharges without inductance) to gradually rising (with considerable inductance in the circuit) did not affect the threshold value of the defibrillating current (Gurvich, Makarychev, Venin, Tabak & Bogushevich, 1972).

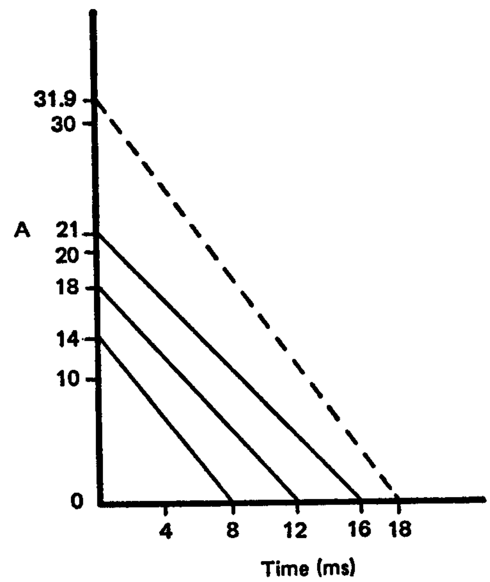

Fig. 2. Diagram showing the dependence of the values of defibrillating current on the duration of the impulse. Aperiodic discharges of condensers with a capacity of 66, 100, 132 and 150 μF were given, and they had durations of 8, 12, 16 and 18 ms respectively.

Response of the heart

It has become obvious that the assumption that the response of the heart to electric stimulation during diastole is the same as that due to defibrillation requires to be modified. Despite the similarity of properties of defibrillation and excitation of the heart which we have established, there are radical differences between these phenomena:

(i) defibrillation of the heart is the result of simultaneous excitation and synchronization of all fibres of the heart;

(ii) defibrillation affects many elements which are in a refractory state.

The necessity to take into account the refractiveness of the fibrillating heart was confirmed by the findings of Brooks, Hoffman, Suckling & Orias, (1955). Decker (1970) commented on the inapplicability of Pflüger's Law during stimulation of the heart in a refractory state. In this state the heart begins to react to stimulation by analectrotonus before recovering the excitability for the appearance of catelectrotonus. This implies that the effect of defibrillation is conditioned primarily by the reaction of the heart to anelectrotonus and not catelectrotonus, i.e. to the rear-front of the wave.

The greater importance of anelectrotonus in cardiac defibrillation explains the diminished effectiveness of triangular impulses and similar aperiodic discharges as their duration is increased, since this results in decreased steepness of the rear-front of the impulse which may be compensated by a corresponding increase in current as was observed here and also by Geddes *et al.* (1970).

The dependence of the effect of summation of both half-waves of the bipolar sinusoidal impulse on the form of the stimulus found by us may also be explained by changes in the rear-front of the impulse during excitation of the heart during defibrillation.

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