mentally by means of somatotropic hormone (Watkins *et al.*, 1956) and pascain (Vinogradov *et al.*, 1957). Garden and Steinhaus (1955) used lidocaine and were successful in 21 of 23 experiments. In their opinion, lidocaine is one of the most effective defibrillators. The drug was injected after a short period of preliminary cardiac massage.

Swann described a case of cessation of ventricular fibrillation after intravenous injection of pronestyl after prolonged cardiac massage. The patient developed fibrillation in the roentgenology department while contrast material was being injected into the aorta. The cardiac activity was restored after 82 min.

Some writers point out that fibrillation develops especially frequently during injection of adrenalin in the course of chloroform anesthesia. In these cases the preliminary injection of antihistamine drugs gave good results (Levitan and Scott, 1949). One further method of preventing fibrillation must be mentioned, bearing a slight relationship to chemical methods of defibrillation. In certain cases hyperventilation of the lungs may also prevent fibrillation (D'Allaines *et al.*, 1955).

Electrical Methods of Defibrillation of the Heart

Defibrillation by Means of an Alternating Current. That the action of a strong electric current could be used to stop fibrillation of the heart has been known for well over half a century. Prevost and Battelli (1899) showed that fibrillation in dogs caused by the action of a low-voltage alternating current (110/220 v) may be terminated by the action of a high-voltage alternating current (2400–4800 v). The electrodes were introduced into the animal's mouth and rectum. If one electrode were placed directly on the surface of the heart fibrillation could be stopped by the action of a current of much lower voltage (220 v).

The possibility of resuscitation by means of the action of a high-voltage current (counter-shock) was studied in different animals in which fibrillation had been induced by means of electric shock (Wiggers, 1936; Hooker *et al.*, 1933; Ferris *et al.*, 1936). The electrodes were placed on the chest wall, on the right and left sides. The fact that a high-voltage current was needed for defibrillation prevented the clinical application of the method. To avoid the risk associated with the use of a high-voltage alternating current, Wiggers recommended thoracotomy in case of the development of ventricular fibrillation so that the electrodes could be applied directly on the heart, and a much lower voltage used. If the ordinary line voltage proved inadequate in these conditions, he recommended repetition of the electric shock at intervals of 1–1.5 sec (the method of serial defibrillation).

During the last decade much research has been carried out into defibrillation of the heart by means of an alternating current, but in spite of this work the technique of application of the alternating current for this purpose has not essentially changed. When fibrillation develops the chest is opened (unless this has already been done at operation), cardiac massage is commenced without delay, and preparations for defibrillation are made. This is done by the direct action of the alternating line current on the heart, through electrodes applied to both sides of the ventricles (Fig. 14). These types of apparatus for defibrillation of the heart (defibrillators) are essentially electric two-way switches allowing the alternating current to act on the heart for the required length of time. The apparatus includes an insulating transformer, the purpose of which is to protect the surgeon himself from the danger of electric shock. Nevertheless, even if such transformers are present, both surgeon and anesthesiologist must take all precautions necessary when the current is switched on. To use Hosler's apt comment, "there is the possibility here of having two candidates for defibrillation instead of one."

For electrical defibrillation to be successful, as a first step the circulation in the coronary vessels must be restored by means of massage. We believe that intra-arterial blood transfusion is particularly effective in overcoming anoxia of the heart before defibrillation. After fibrillation has been abolished, it is often necessary to resume cardiac massage.

When defibrillation is ineffective, cardiac massage should be performed in intervals between discharges, in conjunction with the centripetal intra-arterial injection of aerated blood in small doses. Some authorities recommend injecting 3.5 ml of 1% procaine into the heart in such cases, carrying out injection, massage, and electric shock in turn. If fibrillation persists in spite of these measures, an intracardiac injection of adrenalin may be useful (Beck, Hosler). This paradoxical action of adrenalin is most likely due to its excitatory effect, which may result in the appearance of spontaneous cardiac activity after a second electric shock. As regards procaine, to some extent an adrenalin antagonist, some workers doubt that it has any value and mention the adverse effect of procaine on the tone of the heart muscle and on respiration (Wegria *et al.*, 1953; Stearns *et al.*, 1951; Hosler, 1954, 1956; and others).

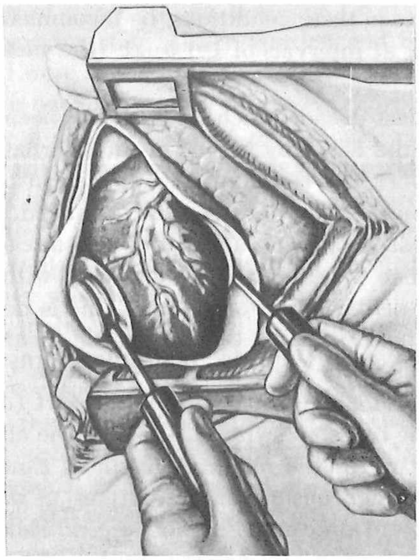

Fig. 14. Position of the electrodes during defibrillation of the exposed heart (after Lacerenza).

Very different views are expressed on the most effective strength and voltage of alternating current to use. American writers consider that a voltage of 110 v (with a current of 1.5–2.0 amp) is sufficient for defibrillation of the exposed human heart, whereas British writers recommend higher voltages. McMillan, for example, suggests starting with an electric shock with a voltage of 130 v, and if this is inadequate, repeating the shock with a higher voltage (150 v); if this too is ineffective, he recommends serial defibrillation (as used by Wiggers) in the form of 4 to 6 shocks in succession, at intervals of 1 sec. If negative results are consistently obtained with this voltage (especially in the case of a large heart), attempts should be made to stop the fibrillation by discharges of 250 v.

The size of the electrodes is very important. The closer their size to the diameter of the heart, the better. Every defibrillator should have electrodes of different diameters, the smallest 5 cm and the largest 8 cm, corresponding to the possible measurements of the heart in different persons. Both electrodes should be concave to provide uniform contact with the surface of the ventricles. The surface of the electrodes must be covered with several layers of gauze soaked in physiological saline.

Defibrillation of the Heart When the Chest is Closed. Zoll and coworkers (1956) have reported defibrillation of the heart through the closed chest wall in 4 patients. They used a defibrillator providing an alternating current of 720 v, and the duration of the discharge was 0.15 sec. One electrode was applied over the left border of the lower end of the sternum, the other over the left anterior axillary line, and defibrillation occurred with a voltage of 360–480 v. Kouwenhoven (1957) applied one electrode over the upper border of the sternum and the other at the level of the apex beat in the left anterior axillary line, and he used a voltage of 480 v for 0.25 sec. For defibrillation in a child aged 6–8 years he recommends half that voltage (240 v). A special switch is incorporated in the apparatus to provide this voltage.

Defibrillation by Means of a Single Electrical Impulse. Critical analysis of the method of application of an alternating current for defibrillation of the heart in experimental and clinical conditions reveals certain inherent disadvantages.

No hard and fast rule has been established regarding the strength and duration of the current to be used. Much of the responsibility for this is due to the interpretation of electrical defibrillation, existing even before the time of Prevost and Battelli, as the result of a temporary loss of the excitability of the heart under the influence of a strong current. This interpretation of the mechanism of defibrillation by the action of an electrical stimulus did not permit the establishment of a regular relationship between the effect of the stimulus and its strength and duration. The essential minimal duration of the stimulus could not be determined. It was thought that the likelihood of success diminished with a decrease in the duration of the current. The hypothesis that the heart must be stopped in order to abolish fibrillation was apparently confirmed by the fact that a similar result may be obtained by the action of potassium salts, quinidine, and procaine on the heart—agents depressing cardiac activity. For the same reason there is no unanimity regarding the optimal duration of the alternating current for fibrillation.

Some progress has been achieved in the study of the mechanism of electrical defibrillation by using single condenser discharges instead of an alternating current (Gurvich and Yun'ev, 1939). The very fact that a single impulse could be effective cast doubt on the notion of defibrillation as the result of loss of the excitability of the heart.*

*The data of Prevost and Battelli on defibrillation of the exposed dog's heart by electrostatic discharges of extremely high voltage (18–20 kv) could not be interpreted at that time as proof that the mechanism of defibrillation was different.

Further investigations produced convincing evidence in favor of a different mechanism of electrical defibrillation. This evidence included the discovery of a regular relationship between the strength and duration of the stimulus during defibrillation (Gurvich, 1957). As regards its time parameter, this relationship was found to coincide with the relationship between the strength and duration of the stimuli exciting the heart during diastole. Testing the action of a defibrillating impulse on the normally contracting heart did not lead to its arrest, but always caused extrasystolic contraction. These findings showed that electrical defibrillation is the result of the ordinary excitatory, rather than the inhibitory, influence of electrical stimulation on the heart tissues. The need for extremely strong stimulation may be explained by the fact that defibrillation takes place as a result of the simultaneous excitation and synchronization of the activity of all the individual fibers of the myocardium and the conducting system. In this way the action of a strong current differs from the action of a weak current, which is incapable of producing simultaneous excitation and, in the case of frequent stimulation, causes excitation of the individual fibers at different times, and thus leads to the development of fibrillation. It was discovered that the differences in the results of the action of a weak and strong current on the heart are due to the involvement of a larger or smaller number of fibers in the process of excitation. This explanation is evidently incompatible with the earlier notions of the diametrically opposite action (excitation or depression) of a strong and a weak current on the heart.*

Using these results as a theoretical basis, an attempt was made to select a single electrical impulse which would exert an effective action on the heart and which would correspond to a current of minimal strength and duration. This duration was roughly equal to the "utilization time" of stimulation of the heart, *i.e.*, about 0.01 sec. Impulses of shorter duration required a much higher voltage, and the use of impulses of longer duration did not permit a lower voltage to be effectively used for defibrillation. The optimal duration of the defibrillation impulses (0.1 sec) was confirmed by tests on the normally contracting heart. The action of such an impulse

* The fact that there is no difference in principle between the reaction of the individual elements of the heart to the action of a current causing or stopping fibrillation is also demonstrated by the fact that when a particular strength of current is chosen fibrillation may be started and stopped merely by changing the rhythm and not the strength of stimulation: 10 stimuli per second caused fibrillation and a lower frequency of stimulation abolished it.

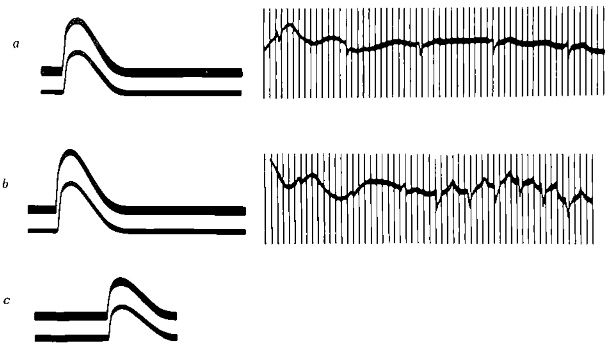

Fig. 15. The action of single impulses on the normal heart. a) Impulses with a current amplitude of 8.5 amp (top oscillogram) do not cause changes in the appearance of the electrocardiogram; b) an impulse with current amplitude of 9.5 amp causes changes in the electrocardiogram; c) the defibrillating impulse has a current amplitude of 6.4 amp.

was not accompanied by changes in the appearance of the ECG (Fig. 15), in contrast to the changes observed after defibrillation by impulses of shorter duration and correspondingly higher voltage.

Impulses of this sort are most conveniently obtained in practice as a discharge from a capacitor of suitable size. However, where it is necessary to use a very strong current and a very high voltage for defibrillation, it is extremely important to limit these as far as possible and thereby to minimize their adverse effect on the heart. This requirement is not satisfied by discharging the capacitor through a circuit consisting mainly of an ohmic resistor. The discharged current under these conditions has a very high initial value, but it is of too short a duration to have the required excitatory effect. Tests on animals showed that it was desirable to remove this high-voltage part of the discharged current by incorporating an inductive resistor in the discharge circuit. The decrease in the amplitude of the current and the simultaneous increase in its duration led to a much more effective discharge and decreased the harmful side-effects of the strong current on the heart (Fig. 16).

A commercially manufactured defibrillator utilizing this principle (Akopyan *et al.*, 1954) has a condenser of capacity 24 μf. The discharge of this condenser through an object (having an ohmic resistance of 50–75 ohms) takes place in this apparatus through an inductance of 0.25 H (active resistance of the coil 25 ohms) (see Fig. 17). In these conditions a rapidly decaying discharge is obtained, with

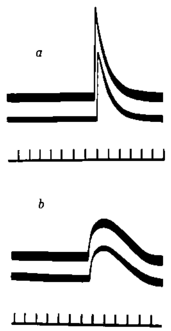

Fig. 16. Comparative values of the current and voltage during defibrillation of the heart by discharges of different form. a) A discharge of 24 μf through a circuit possessing no inductance: current amplitude 15.2 amp, voltage 1150 v; b) discharge of the same capacitor into a circuit possessing inductance: current amplitude 6.4 amp, voltage 550 v.

its first half-period lasting 0.01 sec. Subsequent oscillations in the case of a very rapidly decaying discharge have only negligible amplitude and can have no significant effect on the heart.

A particularly interesting fact is that the voltage and strength of the current defibrillating the heart as a single impulse are practically the same as the voltage and strength of the alternating current required to defibrillate the heart (Fig. 18). This shows that of the total number of periods of the alternating current, in practice the action of only one period is necessary to give the desired effect. It is unnecessary and dangerous to prolong the action of the alternating current beyond the duration of this first period, for it may cause avoidable damage to the heart.

Another advantage of the single impulse is that it is less dangerous than the alternating current. Therefore, if a single impluse is used, a much higher voltage can be applied to defibrillate the heart when the electrodes are placed on the external surface of the unopened chest.

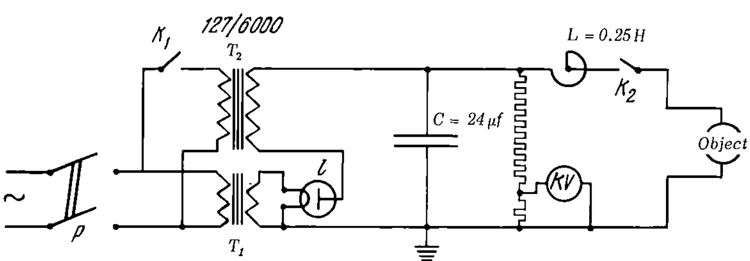

Fig. 17. Diagram showing the principles of the impulse defibrillator. T_2) Step-up transformer; T_1) step-down transformer for heating the kenotron; C) condenser of capacity 24 μf; L) inductance of 0.25 H; K_1 and K_2) switches controlling charging and discharging of the condenser.

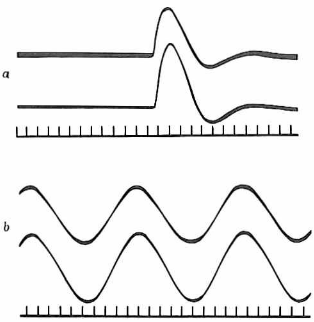

Fig. 18. Comparative values of the current and voltage during defibrillation of the heart. a) With a single impulse (17 amp, 900 v); b) with an alternating current (17 amp, 1000 v) of duration 0.2 sec.

Comparison of the Various Electrical Methods of Defibrillation

When comparing the efficacy of the single impulse and the alternating current it should always be remembered that the difference in voltage during defibrillation of the heart by the condenser discharge and by the alternating current is purely nominal, and in practice the effective voltage applied to the object is roughly the same in both cases. The difference between the nominal voltages is due to the fact that the voltage of the alternating current is designated by its effective value and not by the full amplitude of two half-periods, which will be 2.8 times greater than the effective voltage. In the same way, the discharge of the condenser is designated by the magnitude of the voltage at the terminals and not by the actual amplitude of the voltage of the discharge current which in this case will be, on the other hand, much lower (2.5–3.0 times) than the voltage of discharge. When comparing the values of the voltage of the condenser discharge and the voltage of the alternating current, a correcting factor must be introduced, equal to the product of 2.8×2.5–3.0, roughly 7–8. During defibrillation of the exposed heart by means of the discharge from a condenser with the above characteristics (24 μf, inductance of 0.25 H in the circuit), the condenser must be charged to 1500 v. In this case a discharge impulse is obtained with an amplitude of current and a voltage corresponding to an alternating current of voltage 200–220 v (defibrillation of the heart by means of an alternating current of 110 v is often ineffective, and, according to Hosler, at this voltage the heart has to be squeezed so tightly between the electrodes "that all the blood is expelled from it"). Similarly, it can be calculated that for defibrillation of the human heart, when electrodes are placed on the outer surface of the chest, the condenser must be charged to 3500–4000 v, taking into account Kouwenhoven's results showing that an alternating current

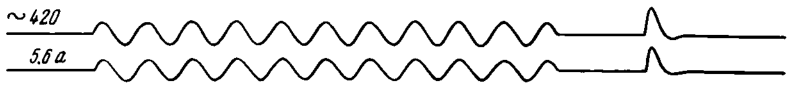

Fig. 19. Oscillograms of current strength and voltage during control measurement on a standard resistance of 420 v alternating current and of a discharge current (capacity 24 μf, inductance 0.25 H) when the potential difference at the condenser is 3000 v.

of 480 v was effective in these conditions. The oscillograms (Fig. 19) clearly demonstrate the close correspondence between the actual voltage and current strength, notwithstanding the very great nominal difference between the values of the voltages of discharge of the condensers (3000 v) and of the alternating current (420 v).

The formulation of the general principles of defibrillation of the heart by means of a single electrical stimulus has led to the development of a rational method of using the electric current for restoring the disturbed cardiac activity. We have already mentioned that this method consists essentially of the application of a single impulse to the heart, equal in duration to the "utilization time" of stimulation of the heart. This duration was shown experimentally to be optimal, a fact which corresponds fully to the general theoretical principles of neuromuscular physiology.

The strict consistency of defibrillation by a single impulse of definite strength confirms that the concept which we have described is correct. Defibrillation by the alternating current often is unsuccessful. We must assume that this is because the voltage was inadequate and the current was applied for too long a period.

It is not accidental, therefore, that as a result of the unsuccessful use of alternating current the idea developed that serial defibrillation must be performed and the voltage increased, as we have mentioned above. If Wiggers used a current of 1 amp and voltage 110 v in defibrillation experiments on healthy dogs, it is natural to suggest that defibrillation of the much larger human heart will require a stronger current and a higher voltage. Alternating current with a voltage of 200–250 v is very likely adequate to abolish ventricular fibrillation in man (this is in agreement with McMillan's [1952] conclusion). An alternating current of this voltage is equivalent in its effective amplitude to the discharge from the condenser of an impulse defibrillator charged to 1500–2250 v. The discharge of a condenser charged to this voltage was found adequate to defibrillate the human heart and was effective at the first application (Smirenskaya and Gel'shtein, 1957).

It remains to say a few words about the duration of the electric shock. At the present time this is very long, and varies within very wide limits: 0.1 sec (Kay and Blalock, 1951), 0.2 sec (McMillan, 1952), 0.25 sec (Kouwenhoven), 0.3 sec (Bigelow), 0.5 sec (Beck), and even 1 sec (Hosler). Beck has reported a very interesting case (Beck *et al.*, 1956) in which an electric shock was applied for 2 sec during defibrillation of the human heart.

How does the very prolonged application of an alternating current affect the result of defibrillating? According to Guyton and Satterfield (1951), an electric shock lasting 0.5–1.0 sec will defibrillate the dog's heart at a voltage roughly 15% below that of an electric shock of shorter duration (0.1–0.2 sec). Gurvich and Zhukov (1957) have shown that a single impulse abolishes fibrillation when the amplitudes of current and voltage used are roughly the same as those effective in defibrillating the heart with an alternating current lasting 0.2 sec. We therefore consider it irrational to attempt to increase the effectiveness of electrical shock by increasing the duration (*i.e.*, the number of impulses) of the alternating current. It is better in such cases to allow a very slight increase in voltage than to lengthen many times over the duration of its action, which is much more harmful to the heart.

What practical conclusions can we reach from our comparison of the results of defibrillation by the various electrical methods? How, in particular, are we to answer the question of whether alternating current may be used, and how should it be used if no impulse defibrillator is available?

We can conclude that in the absence of a safe, impulse type of defibrillator, an alternating current defibrillator may be used. It is important to remember, however, that defibrillation may be performed with the shortest duration of current obtainable with the particular apparatus. With modern alternating current defibrillators, the minimal duration of current provided is usually 0.1 sec, but this is excessively long. We would recommend modifying the apparatus so that it will permit giving current for a period as short as 0.05 sec.* Meanwhile, the voltage of the current should be raised to 220–300 v. Increasing the strength of the electric shock to the heart if the alternating current as originally applied is ineffective

*The most satisfactory solution would be to limit the duration of the alternating current to one complete period. In our recommendation of a duration of 0.05 sec, we take into consideration the relative difficulty of obtaining a more accurate correction of the duration of the alternating current.

must take the form of an increase in the voltage (from 180–200 to 250 v) only, and not of an increase in its duration.

OTHER METHODS OF RESUSCITATION

Electrical Stimulation of the Heart

Hyman (1932) studied experimentally the possibility of maintaining artificially the rhythmic contractions of the heart of a warm-blooded animal by means of electrical stimulation. He applied stimulating electrodes to the region of the sinoauricular node. It was subsequently shown, however, that it is unnecessary to act directly on this particular area of the heart, which is difficult of access. Effective cardiac contractions could be obtained equally successfully by stimulation of any area of the atria or ventricles. The excitation of cardiac activity by means of electrical stimulation of the more superficially situated ventricles is preferable, for this can readily be achieved by placing the electrodes on the surface of the body in the region of the heart. A still more important advantage of electrical stimulation of the ventricles is that this is the only method of stimulating the heart which can be effective in case of complete atrioventricular block. Clinical evidence shows that this disorder, occurring in Stokes-Adams attacks, very often necessitates the use of artificial electrical stimulation of the heart.

The value of electrical stimulation of the heart has recently been studied by many writers (Zoll *et al.*, 1956; Bigelow *et al.*, 1950; Starzl *et al.*, 1955; Just, 1955). In most investigations the electrodes were applied to the outer surface of the chest. Electrical impulses of different shape (saw-tooth and rectilinear) were tested for their ability to produce rhythmic contractions of the heart. The duration of the individual impulses used by different workers varied widely—from 2 to 100 msec. Impulses of 40 to 100 v were effective. These experiments showed that electrical stimulation can sustain the effective action of the heart only in cases of arrest due to a disturbance of conduction or to cessation of automation as a result of vagotropic influences on the heart. In cases of cardiac arrest caused by anoxia or poisoning by anesthetics, electrical stimulation is ineffective. It is interesting that when the heart stops beating as a result of severe cooling of the body, it preserves its excitability and it is able to respond with effective contractions to electrical stimulation (Bigelow and Hopps; Just).

We studied the possibility of using electrical stimulation of the