Transthoracic Ventricular Defibrillation with Triangular and Trapezoidal Waveforms

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ABSTRACT
From 7,200 fibrillation-defibrillation episodes in anesthetized dogs, the effectiveness of 6 classes of unidirectional shocks in reversing ventricular fibrillation of 30-sec duration was determined. The shocks lasted for 1 to 256 usec. Three waveforms (ascending ramp triangular, descending ramp triangular, and trapezoidal) were studied at peak currents of 10 amp and 20 amp. Families of curves of per cent success vs. energy were derived from the data for the 6 classes of waveforms studied and from corresponding curves for 3 classes of unidirectional square-wave shocks previously studied by our group. The families of curves were used as a basis for an analysis of the influence of various parameters on the effectiveness of shocks. We conclude that an appropriate energy content is a necessary, but not sufficient condition for effective ventricular defibrillation, that long, low-amplitude tails on shocks are detrimental and that excessive energy content is detrimental.

ADDITIONAL KEY WORDS energy content of shock electrical stimuli fibrillation refibrillation high power amplifier closed-chest defibrillation cardiac arrhythmias anesthetized dogs

Introduction
The efficacy of various types of transthoracic shocks in reversing ventricular fibrillation and other cardiac arrhythmias has been extensively studied by numerous investigators (1-9). Because the character of the shocks delivered by the conventional or commercial apparatus used in these studies could be varied in only a very restricted fashion, the studies were more useful as a guide to immediate clinical application than for the elicitation of fundamental information concerning the defibrillation process. In 1963, our group described a high-power amplifier designed for fundamental studies, with which the parameters of the shock could be conveniently varied (10), and in 1964 we reported a systematic study of the effectiveness of a variety of square-wave shocks produced by it in reversing ventricular fibrillation (11). An extension of this study to include triangular and trapezoidal waveforms is reported in the present paper.

Methods
The apparatus used to produce triangular and trapezoidal defibrillatory shocks was substantially the same as that previously described (10, 11), except that a negative feedback loop was included around the high-power amplifier to increase the linearity and output impedance of the unit.

Except that triangular and trapezoidal defibrillatory shocks were used instead of square-wave shocks, the experimental procedure was identical to that previously outlined in detail (11). In brief, at least six dogs were used in the evaluation of each waveform. They were anesthetized with pentobarbital sodium, 27.5 mg/kg body weight, injected intravenously. Additional anesthesia, up to 40% of the initial dose, was sometimes required during the procedure.

Ventricular fibrillation was induced with a low-current shock applied through one 9-cm diameter electrode held on the surface of the chest over
the apex of the heart and a similar electrode positioned slightly to the right of midline and somewhat higher on the chest. After 30 sec of fibrillation, the shock under investigation was applied. If defibrillation was achieved on the first trial, the episode was recorded as a success; otherwise it was recorded as a failure and a shock of known high effectiveness was used to save the animal. The minimum interval between the start of two successive episodes of ventricular fibrillation on a given animal was 3 min.

Usually each animal was subjected to 20 fibrillation-defibrillation episodes with a given waveform. However, if it proved impossible to defibrillate an animal after several shocks with the follow-up waveform, external cardiac massage was initiated and the animal replaced by another one. In this way each specific waveform under investigation was evaluated on the basis of 120 episodes with no single animal being involved in more than 20 episodes with a given waveform. After a rest of a day or more, a dog was usually used again in the evaluation of another waveform. Fifty-eight dogs were used in the study.

Results

In Figure 1 the per cent successful defibrillation was plotted against duration for the six classes of waveforms studied. Since the curves are plotted from 60 experimental points, and each point involves 120 trials, the curves summarize 7,200 fibrillation-defibrillation episodes.

The details of the ascending ramp (closed circles) and descending ramp (open circles) triangular waveforms are evident from the sketches in Figures 1a and 1b. The trapezoidal waveforms sketched in Figure 1c are identical to the leading portion of the corresponding 64-msec descending ramp triangular waveforms. However, although the current in the descending ramp triangular waveform decreases linearly for the 64 msec required to reach zero, the linear decay of the current in the trapezoidal waveform is interrupted by a rapid fall to zero at a time corresponding to the specified duration of the shock.

Considerable additional insight into the significance of the experimental results illustrated in one form by the curves of Figure 1 can be obtained by assuming a representative value for the chest resistance and then reploting the curves with energy as the independent variable.

The procedure for reploting the curves can be illustrated by considering the triangular waveform of Figure 3a. The energy in joules delivered by this waveform is given by

\[ U = \int_{0}^{T} i^2R dt, \]  

where \( T \) is the duration in seconds, \( i \) the current in amperes, \( R \) the chest resistance in ohms, and \( t \) the time in seconds. The instantaneous current \( i \) is given by

\[ i = \frac{I_m}{T} t, \]  

where \( I_m \) is the peak current in amperes. When the value of \( i \) from equation 2 is substituted in equation 1, the energy becomes

\[ U = \int_{0}^{T} \frac{I_m^2 t^2 R}{T^2} dt. \]  

The right side of equation 3 may be integrated to yield

\[ U = \frac{1}{3} I_m^2 RT. \]  

If one assumes a representative value of 60 ohms for the chest resistance, equation 4 indicates that a 2-msec, 20-amp, ascending ramp triangular waveform has an energy content of \((20^2 \times 60 \times 2 \times 10^{-3})/3\), or 16 joules. This means, for example, that the 68%, 2-msec point from the curve for the ascending triangular ramp curve of Figure 1b may now be replotted as a 68%, 16-joule point on a curve in which energy is the independent variable. Since equation 4 applies also to the descending ramp triangular waveforms, the smooth curves of Figures 1a and 1b may be easily replotted as the curves of Figures 2a and 2b.

Using the symbols shown in Figure 3b, the energy content of a trapezoidal shock is expressed by

\[ U = \frac{I_m^2 RA}{3} \left[ 1 - (1 - \frac{T}{A})^3 \right], \]  

where \( A = 64 \times 10^{-3} \) sec for the trapezoidal shocks considered in our study. Equation 5

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Relation between per cent success of ventricular defibrillation and duration of (a) 10-amp triangular shocks, (b) 20-amp triangular shocks, and (c) trapezoidal shocks. In (a) and (b) open circles represent results for a descending, and closed circles results for an ascending, ramp waveform; in (c) open circles represent results for a 20-amp, and closed circles for a 10-amp, shock.

**FIGURE 2 (right)**
Relation between per cent success of ventricular defibrillation and energy content of (a) 10-amp triangular shocks, (b) 20-amp triangular shocks, (c) trapezoidal shocks, and (d) square-wave shocks.

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FIGURE 3
Details of triangular and trapezoidal waveforms.

may be used to replot the curves of Figure 1c as the curves of Figure 2c.

For square-wave shocks, the energy content is related to the duration and current amplitude by

\[ U = I_m^2RT. \]  \hspace{1cm} (6)

Equation 6 enables one to obtain the family of curves of Figure 2d from previously published curves which relate per cent success and duration of unidirectional square-wave shocks (11).

The curves of Figure 2 are based on a representative chest resistance of 60 ohms. While it is convenient to make such an assumption, it is by no means mandatory. Substantially the same presentation could have been obtained by using a set of equations derived by dividing both sides of equations 4, 5 and 6 by \( R \) and then plotting per cent successful defibrillation as a function of the independent variable, joules per ohm.

**Discussion**

Limitations of the frequency response of the apparatus as reflected in finite rise and fall times tended to introduce appreciable distortion for triangular and trapezoidal shocks with durations at and below 2 msec. Approximately 0.8 msec was required for the initial peak to be reached in the trapezoidal and descending ramp triangular waveforms. In the trapezoidal and ascending ramp triangular waveforms, the total shut-off time was 1.5 msec, with most of the decrease being completed in 0.5 msec. Residual current before and after the shocks was carefully monitored and never exceeded 20 ma. As previously reported, the distortion of square-wave shocks was significant at and below 1 msec (11). Durations less than 1 msec correspond to energy levels below 24 joules in the 20-amp curve of Figure 2d. The 5- and 10-amp curves of Figure 2d are not carried into the energy range where distortion is a factor.

The effectiveness of a given shock in reversing ventricular fibrillation appears to be a complicated function of the various parameters which may be used to characterize the waveform. Consequently, it is in a somewhat arbitrary fashion that the discussion of the curves of Figures 1 and 2 is divided into considerations of energy content, shape, and current level.

**ENERGY CONTENT**

It is at once apparent from Figure 2 that energy content is an important factor in determining the effectiveness of a shock. Each curve increases, reaches a peak, and then decreases as the energy content is increased. Substantially 100% effectiveness, in those waveforms in which it can be realized, is seen to require a minimum energy level in the neighborhood of 50 to 100 joules. For those waveforms in which 100% effectiveness was not obtained, the peak in effectiveness occurs at...
energy levels in the 25 to 90 joule range. In general, an appropriate energy level is a necessary, but not sufficient condition for effective ventricular defibrillation; other factors must be considered.

**SHAPE**

The 20-amp triangular waveforms of Figure 1b have identical energy content and charge transport for any given duration. Although the curves of effectiveness vs. duration are similar for the shorter duration shocks, they differ dramatically at the longer durations. At 64 msec, the ascending ramp waveform is 96% effective, whereas the descending ramp waveform is substantially 0% effective. The same features are also illustrated in the curves of Figure 2b, where the descending ramp triangular wave has zero per cent effectiveness at the 512-joule level.

These considerations strongly suggest that there may be a mechanism whereby waveforms characterized by long, low-amplitude "tails" defibrillate the heart during the leading portion of the shock and then refibrillate it during the lagging portion of the shock. This hypothesis is further substantiated by the curves for the 20-amp trapezoidal waveforms as illustrated in Figures 1c and 2c. In these figures, the trapezoidal waveform with a duration of 32 msec (448 joules) corresponds to a 64-msec descending ramp waveform from which the last 32 msec (64 joules) have been removed. Such a trapezoidal shock is observed to have an effectiveness of 93%.

The curves for the 10-amp triangular waveforms as illustrated in Figures 1a and 2a are subject to a similar interpretation. Like the 20-amp curves, the 10-amp trapezoidal curves of Figures 1c and 2c further substantiate the hypothesis of defibrillation and refibrillation in waveforms characterized by long, low-amplitude tails.

It has been suggested to us that an alternative hypothesis to the defibrillation-refibrillation thesis is simply that a reasonably sharp fall in current is an essential requirement for defibrillation and because it was absent in the 64-msec descending ramp triangular waves, defibrillation was never truly achieved. Either hypothesis is compatible with the data presented.

**CURRENT LEVEL**

In addition to the rather dramatic role which a low current level seems to play when it enters into a defibrillatory shock as a lagging tail, low current levels appear to detrimentally influence the effectiveness of defibrillatory shocks in more subtle ways.

At the 25-joule energy level, the curves of Figures 2a through 2d suggest that waveforms in which most of the energy is supplied at the higher current levels are more effective than are those waveforms in which an appreciable part of the energy is supplied at the lower current levels. The two 20-amp triangles, the 20-amp square wave, the 10-amp square wave, and the 20-amp trapezoid are waveforms in which either none or very little of their energy is delivered at low current levels (e.g. below 5 amp). All of these waveforms are more than 70% effective at 25 joules. The two 10-amp triangles and the 5-amp square wave represent shocks in which an appreciable part of the energy is delivered at 5 amp or less. At 25 joules, these waveforms are 35 to 50% effective. For unknown reasons, the curve for the 10-amp trapezoidal waveform appears to be abnormally low at the 25-joule point, and consequently it fails to fit into the general pattern. The very low effectiveness of the 20-amp square wave at 12 joules may be a reflection of waveform distortion at 4 msec.

In contrast to the waveforms which yield zero per cent effectiveness at the higher energy levels because of their long, low-amplitude tails, are the remaining waveforms in which the effectiveness appears to decrease more slowly with increasing energy. The 20-amp ascending ramp triangle, the 20-amp square wave, and the 10-amp square wave share the distinction of maintaining very high effectiveness to energy levels of at least 400 to 500 joules. While the effectiveness of the 5-amp square wave falls very rapidly to the neighborhood of 10% for energy levels in excess of 75 joules, the decrease with increasing energy appears to be basically different from
that associated with the long-tail waveforms. The 10-amp ascending ramp triangle falls off much slower than the 5-amp square wave, but considerably faster than the other three waveforms considered in this paragraph. In general, the observed decrease in effectiveness with increasing energy content seems to be less significant in those waveforms in which most of the energy is supplied at the higher current levels than in the waveforms in which an appreciable portion of the energy is supplied at lower current levels.

Conclusions

In unidirectional shocks, an appropriate energy content is a necessary, but not sufficient condition for effective ventricular defibrillation. Substantially 100% effectiveness, in those waveforms in which it can be achieved, requires a minimum energy level of 50 to 100 joules. Long, low-amplitude tails on shocks have a particularly detrimental influence on their effectiveness as a consequence of a mechanism which appears to involve re-fibrillation of the heart after defibrillation has been achieved by the leading portion of the shock. Excessive energy also has a detrimental influence on the success of the shock.

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References

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