Transthoracic Ventricular Defibrillation in the 100 kg Calf with Unidirectional Rectangular Pulses

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SUMMARY The effectiveness in reversing ventricular fibrillation of 30 seconds duration of unidirectional rectangular-wave shocks having pulse widths of 0.5 through 64 msec, pulse amplitudes of 35, 50, 70, 100, and 140 amp, and pulse energies of 109 through 1,660 J was studied in 3,303 transthoracic fibrillation-defibrillation episodes in 100 kg calves. A total of 38 animals were used in the study. Postdefibrillation electrocardiograms were recorded. Families of curves of percent successful defibrillation vs pulse duration, percent successful defibrillation vs pulse energy, duration of postdefibrillation complete block or standstill vs energy, and time required for a return to normal sinus rhythm vs energy were derived. The most effective waveform studied (70 amp — 8 msec — 862 J) yielded defibrillation on the initial attempt in 93% of 120 episodes. In general, the duration of complete block or standstill and the time required for a return to normal sinus rhythm increased with increasing pulse current and pulse energy.

ALTHOUGH THE ENERGY SUPPLIED by most presently available commercial defibrillators is generally adequate for satisfactory transthoracic ventricular defibrillation of small and medium sized patients, there is considerable controversy concerning the energy requirements for a defibrillator intended for large and very large patients. Based upon the results of their laboratory studies involving nonhuman subjects weighing 2.3–340 kg, a review of defibrillation experience at the teaching hospitals of the Baylor College of Medicine and of the Mayo Clinic, and a survey of the literature, Geddes, Tacker, and colleagues have generally argued for defibrillators with higher energy output capabilities. They have recommended, for example, dosage levels of 6.6 or more J/kg body weight for patients weighing over 46 kg. Pantridge and colleagues and Crampton and Hunter, on the other hand, have stressed the operational advantages of small defibrillators. Pantridge et al. have presented clinical evidence to suggest that even when operated considerably below its maximum energy level (400 J stored, approximately 330 J delivered), and particularly when multiple shocks are used, the Belfast defibrillator can be effective in larger patients. Crampton and Hunter have reported successful low-energy transthoracic defibrillation in a limited number of patients. Each of the three groups was concerned about the possibility of myocardial damage from defibrillatory shocks of excessive energy.

The present paper, based on a total of 3,303 fibrillation-defibrillation episodes in 38 animals, is a report of a systematic experimental study of the effectiveness of unidirectional rectangular-wave pulses in achieving transthoracic defibrillation of 100 kg calves. The study, which serves to complement our earlier rectangular-wave studies in dogs, may have important implications for the defibrillation of large human patients.

Methods

Equipment

Described in detail elsewhere, the ultrahigh-energy hydrogen thyratron/silicon controlled rectifier research defibrillator which was used in the study contains three voltage sources. The first is a 60 Hz supply of adjustable
amplitude and duration. The second source uses an 18,000 J capacitor bank which can be charged to 800, 1,600, or 2,400 V. Silicon controlled rectifiers in series with the chest are used for initiating the discharge and silicon controlled rectifiers shunting the capacitor bank are used for terminating the discharge. The third source employs another 18,000 J capacitor bank which can be charged to 5,000, 10,000, or 15,000 V. Large ceramic-envelope hydrogen thyatrons are used for initiating and terminating the discharge. In our study, fibrillation was induced with the first source, the waveform being evaluated was supplied by one of the other two sources, and the remaining source delivered a highly effective follow-up shock to salvage the animal in the event the waveform under study failed to defibrillate.

A high voltage relay, synchronized with the operation of the defibrillator, disconnected the electrocardiographic monitoring apparatus from the animal while the capacitor bank was being charged and the shock delivered to the animal and then reconnected the monitoring apparatus after the shock was delivered. Waveforms of both the current and the voltage of the shock being evaluated were observed on a Tektronix model 5031 dual-beam storage oscilloscope. For most of the waveforms studied, there was little droop in either the current or voltage waveforms and the pulses appeared quite rectangular. The largest droop by far, of about 14%, was associated with the 35 amp — 64 msec waveform of current. From values observed at the midpoint of the waveforms, chest resistance was calculated as the ratio of voltage to current and delivered energy was calculated as the product of voltage, current, and pulse width. The lead II electrocardiogram was observed on a Hewlett-Packard model 130-C oscilloscope and recorded with a Sanborn model 500 electrocardiograph. With manual positioning of the recorder stylus, suitable electrocardiographic records were nearly always obtained within 1 1/2 to 2 1/2 seconds of the shock.

Procedure

At least six 100 ± 10 kg calves of random breed and random sex were used to evaluate the effectiveness in achieving defibrillation and the nature of the post-defibrillation electrocardiogram of each of the 27 types of shocks studied. The unfasted and unpremedicated animal was secured to the vertical tilt table with slings, anesthetized by rapid injection via the external jugular vein of 110 mg/kg glyceryl guaiacolate (100 mg/ml) and 4.4 mg/kg thiopental sodium in 5% dextrose. The table was then rotated to a horizontal position. After direct oral intubation, anesthesia was maintained in a closed system with methoxyflurane in 50% N2O and 50% O2 following low-dose guidelines with automatic assisted ventilation. The anesthesia techniques used in this study were derived from methods employed by Garner et al. and Weingarten and Lowe. Stainless steel electrodes, 13.0 cm in diameter, were covered with Redux paste and held in position on the anterior portion of the clipped chest by rubber straps. The left electrode was over the apex of the heart and the right electrode to the right of midline and higher on the chest. In selecting the electrode diameter, we would have liked to scale from the electrode diameter used in our study in dogs by making the diameter proportional to the cube root of body weight or 15.6 cm. However, it was necessary to reduce this figure slightly in order to achieve full contact between the electrodes and body surface with the straps which were used. These electrodes are considerably larger than those customarily used in clinical applications.

After the animal was prepared and securely restrained in right lateral recumbency, the research defibrillator was used to administer a 1 sec, 60 Hz, 94–120 V shock through the chest electrodes to induce ventricular fibrillation as verified with the monitoring oscilloscope. After 30 sec of fibrillation, the shock being evaluated, supplied by one of the two voltage pulse generators in the defibrillator, was applied to the chest electrodes. If defibrillation was achieved on the first trial, followed by survival without the necessity for external massage, the episode was tabulated as a success and the resulting electrocardiogram was recorded for 2 1/2 min. The evaluation of the electrocardiogram was later performed by one of us without prior knowledge of the parameters of the shock. If defibrillation was not achieved on the first trial with the shock being evaluated, a shock of known high effectiveness, supplied by the other voltage pulse generator in the defibrillator, was used to defibrillate the animal, the episode was tabulated as a failure, and the resulting electrocardiogram was not recorded. In either event, the procedure was repeated with not less than 3 min between the start of successive episodes.

Our overall study was divided into two parts: first, the primary investigation which involved 3,240 fibrillation-defibrillation episodes and, second, a limited supplementary investigation involving 63 fibrillation-defibrillation episodes. Procedural details which apply to our primary study are outlined in the present paragraph; details which apply to our supplementary study are covered in the next paragraph. Usually, each animal was subjected to 20 fibrillation-defibrillation episodes with a given waveform. However, some series were terminated with fewer than 20 episodes because external cardiac massage or other resuscitative efforts were needed, there was obvious deterioration in the cardiac status of the animal, or because death ensued. When this happened, more than six animals were needed for the evaluation of a given waveform. In any event, each of the specific waveforms 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 calf was ordinarily used again in the study of a different waveform which might or might not involve the same current amplitude: no effort was made to use the same calves for all of the durations associated with a given level of current.

In our supplementary study, the effectiveness of 35 amp shocks with durations of 32, 45.3, and 64 msec was studied in a procedure in which each of three calves was carried through a series of 21 fibrillation-defibrillation episodes. The episodes involving the different pulse durations were interlaced in such a way that the 1st, 4th, 7th, 10th, 13th, 16th, and 19th episodes in each calf involved pulses of 32 msec duration; the 2nd, 5th, 8th, 11th, 14th, 17th, and 20th episodes in each calf involved pulses of 45.3 msec duration; and the 3rd, 6th, 9th, 12th, 15th, 18th, and 21st episodes in each calf involved pulses of 64 msec duration.

In our overall study, which involved a total of 38 calves with an average of 87 fibrillation-defibrillation episodes per calf, a calf was never used in more than 300 fibrillation-
defibrillation episodes or when its weight dropped below 90 kg or exceeded 110 kg.

Results

The relevant results obtained in our primary study of rectangular-wave shocks involving 27 pulse amplitude — duration combinations are summarized in table 1. The third column of the table requires some explanation. The energy delivered by a rectangular pulse is given by the product of current squared, time, and chest resistance. If chest resistance is constant, the delivered energy is proportional to current²-time. Thus current²-time is a significant descriptor of a pulse. The entries in the third column are useful in that they are exactly proportional to the energy which would be delivered to a constant resistance and roughly proportional to actual delivered energy in our primary study. Because the observed incidence of postdefibrillation standstill was so very low in all types of shocks, data related to the duration of standstill were grouped with those for complete block in arriving at the entries for the column in the table headed "Average duration of complete block or standstill." The entries in this column were obtained by dividing the sum of the values for the duration of block or of standstill associated with each individual episode in which defibrillation was achieved by the number of successful defibrillations. A similar averaging technique was used for obtaining the entries in the final column. When, as occasionally happened (in 30 episodes — four episodes with the 70 amp-4 msec shock, one episode with the 100 amp-2 msec shock, two episodes with the 100 amp-8 msec shock, 11 episodes with the 140 amp-1 msec shock, five episodes with the 140 amp-2 msec shock, and seven episodes with the 140 amp-4 msec shock), normal sinus rhythm had not returned in the electrocardiogram at the end of our 2½ min recording period, a figure of 150 sec was used in the averaging process from which the entries in the final column of the table were derived.

A family of curves relating the percent success in achieving defibrillation and the duration of the shock is shown in figure 1. With the exception of the 35 amp data, the data points appear to define smooth curves. There seems to be an anomaly in the behavior of some of the data from the 35 amp primary study (indicated by square symbols). Specifically, the percent success value associated with the 45.3 msec pulse duration appears large in comparison with the corresponding values associated with the two neighboring points. The supplementary study was designed to test whether this behavior represented an actual jump in effectiveness of the shock in going from 32 to 45.3 msec duration or reflected chance variation associated with the calf selection procedure in the design of the primary study. The supplementary study yielded 62% success in achieving ventricular defibrillation at 32 msec, 57% success at 45.3 msec, and 33% success at 64 msec. These data are indicated by the + symbol in figure 1. While not particularly persuasive as to the exact percent success levels associated with the various

![Figure 1](http://circ.ahajournals.org/)

**Figure 1. Relationship between percent success of ventricular defibrillation and duration of shocks. The + symbols represent data from our supplementary study involving 35 amp shocks.**
pulse durations, these data from the supplementary study do strongly favor the alternative hypothesis that the apparent anomalous behavior of the data from the primary study is a chance phenomenon which does not reflect an actual jump in effectiveness for shocks having a pulse duration of 45.3 msec. The 35 amp curve, as sketched in figure 1, is based upon data from both the primary and supplementary studies. A family of curves relating the percent success in achieving defibrillation and the delivered energy content of the shock is shown in figure 2. As in figure 1, the + symbol is used for data from the supplementary study and the 35 amp curve is based upon data from both the primary and supplementary studies.

As indicated in table 1, the incidence of an interval of "complete block," that is, only P-waves with no ventricular activity, is quite high and that of standstill is very low in the postdefibrillation period for almost all types of shocks. Consequently, these descriptors are not as useful as is the average duration of complete block or standstill in characterizing the effects of the different types of shocks on the postdefibrillation electrocardiogram. Data relating the average duration of complete block or standstill and the delivered energy at the different current levels are presented graphically in figure 3. The average time to return to normal sinus rhythm is another descriptor which characterizes and differentiates the effects on the postdefibrillation electrocardiogram of the different types of shocks. The relationship between the average time to return to normal sinus rhythm, the delivered energy, and the current amplitude is shown in figure 4.

In figure 3, there are five data points (one from each of the five current levels) which lie within an energy range of 392 to 475 J. The current squared-time values in table 1 for the waveforms associated with these five points are virtually identical (19.6–20.0 amp²-sec). There are similar groupings of five points each in the neighborhood of 200 J (9.8–10.0 amp²-sec), 800 J (39.2–40.0 amp²-sec), and 1,600 J (78.4–80.0 amp²-sec). Similar comments apply to the data in figure 4. By pooling the data within each of these groups, the relatively smooth curves shown in figure 5 are obtained where the horizontal lines represent the range of the energy values which are grouped and the solid circular symbols represent the average of the energy values within the respective groups. One may also pool data on the basis of current level. When the same data are pooled on this basis, the presentation shown in figure 6 results. Here, each of the plotted points represents the pooled data from the four energy range levels.

**Discussion**

In a recent paper,15 we derived a set of explicit and internally consistent relationships for extrapolating or scaling defibrillation experience with one size of animal to a larger animal of the same species. In a formal way, these relationships allow us to size-scale our extensive experience in dogs4–8 for comparison with our experience in calves.

From the families of curves in figures 1 and 2, it appears that the most effective rectangular-wave shock is one having a current amplitude of approximately 70 amp, a pulse duration of about 8 msec, and an energy content in the neighborhood of 800 J. These values are generally comparable to those obtained by size-scaling from our ex-
perience in dogs. It is of interest that equations associated with Geddes and Tacker's threshold curves for defibrillation of animals with heavily damped sine waves yield energy levels of 800 and 814 J for 100 kg animals.\textsuperscript{2,3} Defibrillation effectiveness in our calves decreases rather slowly with decreasing pulse duration and pulse energy: for 70 amp shocks, the 50\% effectiveness level is reached at a pulse duration of slightly less than 2 msec and with a pulse energy content of 200 J.

In some respects, the data presented in figures 1 and 2 contrast sharply with our experience in dogs. In our calves, we were able to achieve a peak success level of only 93\%. In our dog studies, peak success levels of 100\% were realized. From figure 2, it is evident that at, for example, the 800 J pulse energy level, the percent of success in achieving ventricular defibrillation falls rapidly as we move either way from the optimal pulse amplitude level of 70 amp. In our dog work, on the other hand, the curves of percent success vs the energy content of the shock tend to be more closely grouped and the percent success in achieving ventricular defibrillation decreases slowly as we move away from the optimal pulse amplitude level.

Electroshock-induced cardiac arrhythmias in the dog have been extensively investigated. Most studies have involved arrhythmias induced by a capacitor discharge through the chest\textsuperscript{10} or by a discharge circuit in which an inductor is in series with the capacitor.\textsuperscript{14-16} Our own earlier study utilized rectangular-wave shocks.\textsuperscript{8} These various studies indicated that the incidence and severity of the induced arrhythmias are functions of the drugs administered to the experimental animal and of the current amplitude and energy content of the defibrillatory shock.

In broad terms, the increase in arrhythmic activity in the calf with increasing current amplitude and energy content of the shock as indicated in figures 3, 4, 5, and 6 is similar to that observed in dog studies. However, postdefibrillation block as indicated in figures 3, 4, 5, and 6 does appear to be much more pervasive in our rectangular-wave study in calves than in our rectangular-wave study in dogs. From table 1, we see either a high or very high incidence of complete block in the postdefibrillation electrocardiograms associated with each of the listed types of shocks except for the 35 amp — 4 msec and 35 amp — 8 msec waveforms. In contrast, size-scaled data from our dog study suggest that in hypothetical dogs the size of our calves there should be a zero or very low incidence of complete block at current levels of 35, 50, and 70 amp and for the shortest duration shocks at the 100 and 140 amp levels.

Although there are some discrepancies, the general agreement between our dog and calf data give some credence to the procedure of extrapolating experience from one species to another. To the extent that such an approach is valid, the results of the present study together with the results of our earlier study in dogs would seem to have the following implications for clinical defibrillation. 1) For those applications in which easy portability is not of primary concern, the availability of higher energy defibrillators than those commonly manufactured today would be desirable. 2) When easy portability is of major importance, 300 to 400 J defibrillators should prove relatively effective. 3) For optimal defibrillation of patients of a given size, specifying only the energy content of the delivered shock is not sufficient; current amplitude or, alternatively, pulse duration must also be specified. 4) When defibrillators are to be used with patients of widely different weights, optimum results should be obtained by keeping the pulse duration relatively invariant and letting the current amplitude vary with the two-thirds power of body weight.

**References**

A Comparison of Unipolar and Bipolar Electrograms for Cardiac Pacemaker Sensing

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SUMMARY Simultaneous unipolar and bipolar electrograms were recorded and compared from 49 pacemaker patients with bipolar endocardial electrodes. Average bipolar depolarization signal voltage equaled that of unipolar but showed greater variation. Bipolar and unipolar slew rates were equal in both mean and variance. The proximal pole voltage had little effect on the bipolar result in 8% of the cases, tended to cancel the tip voltage in 49% of the cases and augmented the tip voltage in 43% of the electrograms.

FROM THE FIRST DAYS of cardiac pacing, two varieties of stimulating electrodes have been used: unipolar and bipolar. The unipolar electrode has one pole (cathode or negative stimulating pole) in contact with cardiac tissue, and the other (anode or positive pole) outside of the heart, either in subcutaneous tissue or on the surface of the body. The bipolar electrode has both the cathode (sometimes called its distal or tip pole) and the anode (proximal or ring pole) at the cardiac tissue being stimulated.

The same electrodes are used to sense cardiac activity as well as to stimulate the heart. Bipolar and unipolar electrodes are not equivalent in transmitting the cardiac electrogram to the pacemaker. Only the electrical events at the tip pole describe the unipolar electrogram; the remote anode contributes negligible voltage, since its location is extracardiac. The bipolar electrode exhibits a large anodal voltage (ring signal), similar in magnitude to the tip signal, but the resulting electrogram is also dependent upon the orientation of the electrode within the heart. It has long been demonstrated that unfavorable electrode orientation can produce low voltage bipolar signals, even in the presence of high voltage tip and ring signals.

The average bipolar R wave duration was 28% less, the T wave amplitude 34% less, and the ST-segment elevation 37% less than the unipolar values.

By consistently attenuating the undesirable T waves and ST elevations, while leaving the depolarization signal unaffected, the bipolar electrode offered the advantage of a superior signal-to-noise ratio for sensing depolarization. In one case, however, the bipolar signal was so small as to cause a clinical sensing failure.

The unipolar system is not orientation sensitive, because of its virtually indifferent anode, and has been considered to yield larger and morphologically consistent electrograms. The preference for unipolar sensing is such that, in the event of unsatisfactory bipolar sensing, conversion to unipolar is frequently attempted.

Several clinical instances in which bipolar sensing was superior to unipolar, or in which conversion from bipolar to unipolar produced no beneficial effect, caused a re-evaluation of the previously held beliefs. The difference between the two electrograms was evaluated by measuring and recording signals returning via the pacemaker electrode during implant (acute) and during pulse generator replacement (chronic) on satisfactorily functioning bipolar electrodes. The signals compared were, in each case, the unipolar signal from the tip pole, and the bipolar signal developed between tip and ring poles.

Methods

Right ventricular, high fidelity (0.1Hz - 2kHz) endocardial electrograms from bipolar pacemaker electrodes were measured in 49 patients. Twenty-one electrodes were acute and 28 were chronic (in service 2-83 months). A three-channel lead selector and high impedance isolated preamplifier of
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