TRANSTHORACIC DEFIBRILLATION OF 100 KG CALVES WITH BIDIRECTIONAL TRUNCATED EXPONENTIAL SHOCKS

J. C. Schuder, W. C. McDaniel, and H. Stoeckle

High-intensity electric field stimulation causes periods of arrest in cultured myocardial cells. Jones and Jones have shown that the duration of arrest caused by stimulation with a unidirectional rectangular pulse may be reduced by the addition of a low-amplitude reverse polarity pulse to the waveform[1] and that the ratio of field intensity required to produce a given duration of arrest to that needed for cellular excitation tends to be larger for damped sinusoidal waveforms having a reverse current component than for unidirectional waveforms[2]. These findings suggest that the inclusion of a reverse current component in a defibrillatory waveform might reduce post-shock arrhythmias without having an adverse effect upon the level of successful defibrillation. On the contrary, Niebauer and colleagues have compared the efficacy and safety of unidirectional and bidirectional low-droop trapezoidal (nearly rectangular) waveforms in defibrillating isolated perfused canine hearts and concluded that symmetrical bidirectional waveforms offer no significant efficacy or safety advantage over unidirectional pulses[3].

A comparison of the results of studies by our group of the effectiveness of one-cycle, symmetrical, bidirectional, rectangular wave shocks[4], one-cycle, asymmetrical, bidirectional, rectangular wave shocks[5], and unidirectional rectangular wave shocks[6] in the transthoracic defibrillation of 100 kg calves indicates that the most successful of the symmetrical and asymmetrical bidirectional waveforms are more successful and require less energy than the most successful unidirectional waveform.

While rectangular wave shocks are very convenient for defibrillation research because the various parameters can be so easily and unambiguously specified, they are technologically difficult to generate in clinical sized defibrillators. In the present paper, we describe a study of the effectiveness of a category of symmetrical and asymmetrical truncated exponential waveforms, which can be implemented in clinical sized apparatus, in the transthoracic defibrillation of 90-110 kg calves.

METHODS

Waveform Selection. A generalized representation of the category of waveforms considered in this paper is shown in Figure 1. The leading and lagging portions of the waveform have identical time constants, τ, and identical durations, T. The amplitude of the initial current of the leading half-cycle of the waveform, I, is 70 amp in all cases. We define the fractional undershoot associated with this category of waveforms as

$$f = |I_3/I_1| = |I_4/I_2| \qquad \text{Equation 1}$$

where the vertical lines denote absolute value.

The energy in joules delivered by a waveform of current of the type shown in Figure 1 is given by

$$U = 0.5\, R\, \tau\, [(I_1^2 - I_2^2) + (I_3^2 - I_4^2)] \qquad \text{Equation 2}$$

which, together with Equation 1, yields

$$U = 0.5\, R\, \tau\, (I_1^2 - I_2^2)\,(1 + f^2) \qquad \text{Equation 3}$$

where R is the chest resistance in ohms, τ is in seconds, and the I's are in amperes.

Solving Equation 3 for τ gives

$$\tau = \frac{2U}{R\,(I_1^2 - I_2^2)\,(1 + f^2)} \qquad \text{Equation 4}$$

Furthermore,

$$T = \tau\, \ell n\, (I_1/I_2) \qquad \text{Equation 5}$$

From Equations 4 and 5, one can determine the time constant and duration required to deliver a specified energy level, U, to a chest having a given resistance, R, with a waveform having specified values of I_1, I_2, and f.

From the Departments of Surgery and Child Health, University of Missouri, Columbia, Missouri.
Supported by grant HL-18040 from the National Heart, Lung, and Blood Institute and a grant from Physio Control Corporation.

The I_1, I_2, f, and U values used in the 8 waveforms evaluated in the present study were selected so that the results for each specific waveform could be compared easily with results obtained previously with bidirectional rectangular waveforms[4,5] having amplitude, fractional undershoot, and delivered energy values of I_1, f, U and I_2, f, U.

As an example, the rectangular waveform shown in Figure 2b has a leading half-cycle amplitude equal to the initial amplitude of the leading half-cycle of the exponential waveform sketched in Figure 2a: the waveform shown in Figure 2c has a leading half-cycle amplitude equal to the final amplitude of the leading half-cycle of the waveform shown in Figure 2a. The 3 waveforms in Figure 2 have identical undershoots and deliver the same energy.

The specifications for the 8 waveforms which were evaluated are shown in Table I. In this table, the durations tabulated in the fourth and eighth columns are calculated from Equations 4 and 5. In some cases, the levels of current listed in columns 6 and 7 are experimental target values which have been rounded to the nearest integer from their theoretical noninteger values.

TABLE I. DESCRIPTION OF BIDIRECTIONAL EXPONENTIAL WAVEFORMS

Waveform No.	Leading Half-Cycle Current I_1 amp	I_2 amp	Leading Half-Cycle Duration T msec	Fractional Undershoot f	Lagging Half-Cycle Current $-I_3$ amp	$-I_4$ amp	Lagging Half-Cycle Duration T msec	Delivered Energy U joules
1	70	35	3.77	1/2	35	18	3.77	250
2	70	35	3.77	1	70	35	3.77	400
3	70	50	2.80	1/2	35	25	2.80	250
4	70	50	2.80	1	70	50	2.80	400
5	70	35	7.54	1/4	18	9	7.54	425
6	70	35	7.54	1/2	35	18	7.54	500
7	70	50	5.61	1/4	18	13	5.61	425
8	70	50	5.61	1/2	35	25	5.61	500

Delivered energy values are based upon an assumed representative chest resistance of 20 ohms.

Equipment. A bidirectional waveform research defibrillator, which has been described elsewhere[7], was used to supply a low current shock for inducing fibrillation, the bidirectional exponential waveform being evaluated (or a screening bidirectional rectangular wave shock), and an effective follow-up shock to salvage the animal in case the waveform being evaluated did not yield defibrillation. Current and voltage waveforms of the shock being evaluated were displayed on a Tektronix model 5113 dual-beam storage oscilloscope. The chest resistance of the bidirectional exponential waveforms was calculated as the arithmetic mean of the voltage to current ratios evaluated near the midpoints of the 2 half-cycles. Lead II electrocardiograms were displayed on an oscilloscope and recorded with an electrocardiograph for later evaluation.

Procedure. Before being entered into our detailed study, calves were screened by requiring that successful first-shock defibrillation be achieved in at least 19 out of 20 defibrillation attempts with a bidirectional rectangular wave shock having a leading half-cycle amplitude of 50 amperes, a leading half-cycle duration of 8 msec, a fractional undershoot of 1/2, and a nominal delivered energy of 500 joules. Fourteen calves passed the screening requirement and were used in our detailed study: one calf failed the screening test.

The procedure used in our detailed study was almost identical to that previously described[6]. Briefly, the calves were anesthetized with 110 mg/kg glycerly guaiacolate and 4.4 mg/kg thiopental sodium injected intravenously, intubated, and maintained with methoxyflurane in 50% N_2O and 50% O_2. Fibrillation was induced with a low current transthoracic shock and, after 30 secs, the shock being evaluated was applied. If defibrillation was achieved on the first trial, it was recorded as a success and the electrocardiogram recorded for 2-1/2 mins. Otherwise, the shock was recorded as a failure and a shock of known high effectiveness used to defibrillate the animal. The procedure was repeated with not less than 5 mins between the start of successive episodes. Each specific waveform was evaluated on the basis of 120 episodes in 90-110 kg calves with no animal being involved in more than 20 episodes in a given session or more than 20 episodes with a single waveform. Our detailed study encompassed a total of 120 x 8 = 960 fibrillation-defibrillation episodes.

RESULTS

The results are summarized in Tables II and III. The experimental chest resistance values tabulated in Table II indicate a limited variation in chest resistance for the shocks evaluated and serve to justify the use of 20 ohms as a representative value of chest resistance.

TABLE II. BODY WEIGHT AND CHEST RESISTANCE OF CALVES

Waveform No.	Body Weight kg	Chest Resistance ohms
1	103 ± 6	20.3 ± 1.3
2	102 ± 5	20.3 ± 1.3
3	102 ± 3	19.9 ± 2.0
4	102 ± 4	19.7 ± 1.7
5	100 ± 3	19.5 ± 2.1
6	101 ± 2	19.3 ± 2.2
7	101 ± 4	19.9 ± 2.1
8	102 ± 4	18.6 ± 1.4

Entries for body weight and chest resistance are means ± SD and based upon 120 episodes.

TABLE III. RESULTS OF BIDIRECTIONAL WAVEFORM SHOCKS

Waveform No.	Successful Defibrillations No.	%	Time Required for Appearance of First Ventricular Complex secs	Time Required To Return To Normal Sinus Rhythm secs
1	108	90	3.0 ± 1.0	9.4 ± 6.4
2	113	94	6.1 ± 3.8	26.2 ± 15.5
3	109	91	3.1 ± 1.4	12.7 ± 9.4
4	117	98	5.2 ± 3.9	28.4 ± 17.4
5	104	87	8.3 ± 8.3	17.7 ± 10.7
6	115	96	6.1 ± 5.0	16.7 ± 14.1
7	119	99	6.2 ± 4.7	9.8 ± 5.4
8	120	100	9.7 ± 9.6	21.8 ± 17.0

Entries for the appearance of the first ventricular complex and for the return of normal sinus rhythm are means ± SD and based upon the indicated number of successful defibrillations.

In Figure 3 is plotted percent success versus delivered energy for the 4 exponential waveforms in which the initial half-cycle current sweeps from 70 to 35 amperes. In Figure 4 are plotted the corresponding data for the 4 waveforms in which the initial half-cycle current sweeps from 70 to 50 amperes. Two short line segments are associated with each of the 8 datum points. These segments represent the percent success observed previously for bidirectional rectangular wave shocks[4,5] having the fractional undershoot of the exponential waveform and leading half-cycle current amplitudes equal to the initial and final values respectively of the leading half-cycle of the exponential waveform.

In calves, there is often an appreciable period of standstill or of only p-waves in the electrocardiogram following a defibrillatory shock. Data from the fourth column of Table III, along with corresponding data from earlier studies with bidirectional rectangular waveforms[4,5] are plotted in Figures 5 and 6. Similar graphs relating the time required for a return of normal sinus rhythm in the electrocardiogram could be constructed from data in the final column of Table III and our earlier studies[4,5].

DISCUSSION

The predominant tendency for each of the percent success levels of the bidirectional exponential wave shocks under evaluation to fall within, on, or very close to the boundaries defined by the 2 associated bidirectional rectangular wave shocks, as illustrated in Figures 3 and 4, supports the proposition that such shocks are well behaved and that their performance is approximately predictable from that of the associated bidirectional rectangular wave shocks. This proposition is further strengthened by the data concerning the shock induced electrocardiographic disturbances as shown graphically in Figures 5 and 6 and by a comparison of the data in column 5 of Table III with corresponding rectangular wave data developed earlier[4,5]. The most successful of the bidirectional exponential waveforms evaluated (100%) was equivalent to the most successful bidirectional rectangular waveform[5] (100%) and superior to the most successful unidirectional rectangular[6] (93%) and unidirectional truncated exponential[8] (94%) waveforms in achieving ventricular defibrillation in our 100 kg calves.

Although there are inherent uncertainties in trying to extrapolate experimental experience from the 100 kg calf to the human, we interpret the results of this and our earlier studies[4-6,8] as warranting clinical trials of bidirectional truncated exponential wave defibrillators.

REFERENCES

1. Jones JL, Jones RE. Decreased arrhythmias in cultured myocardial cells following high intensity electric field stimulation with biphasic rectangular waveforms. Fed Proc 42:1114, 1983.
2. Jones JL, Jones RE. Improved defibrillator waveform safety factor with biphasic waveforms. Am J Physiol 245:H60, 1983.
3. Niebauer MJ, Babbs CF, Geddes LA, Bourland JD. Efficacy and safety of the reciprocal pulse defibrillator current waveform. Med Biol Eng Comput 22:28, 1984.
4. Schuder JC, Gold JH, Stoeckle H, McDaniel WC, Cheung KN. Transthoracic ventricular defibrillation in the 100 kg calf with symmetrical one-cycle bidirectional rectangular wave stimuli. IEEE Trans Biomed Eng BME-30:415, 1983.
5. Schuder JC, McDaniel WC, Stoeckle H. Defibrillation of 100 kg calves with asymmetrical, bidirectional, rectangular pulses. Cardiovasc Res (in press).
6. Gold JH, Schuder JC, Stoeckle H, Granberg TA, Hamdani SZ, Rychlewski JM. Transthoracic ventricular defibrillation in the 100 kg calf with unidirectional rectangular pulses. Circulation 56:745, 1977.
7. Schuder JC, Gold JH, McDaniel WC. Ultrahigh-energy hydrogen thyratron/SCR bidirectional waveform defibrillator. Med Biol Eng Comput 20:419, 1982.
8. Schuder JC, Gold JH, Stoeckle H, Granberg TA, Dettmer JC, Larwill MH. Transthoracic ventricular defibrillation in the 100 kg calf with untruncated and truncated exponential stimuli. IEEE Trans Biomed Eng BME-27:37, 1980.

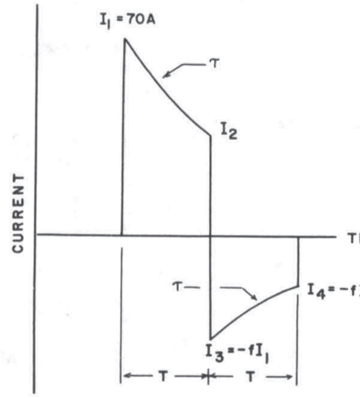

Figure 1. Generalized representation of category of bidirectional truncated exponential waveforms studied.

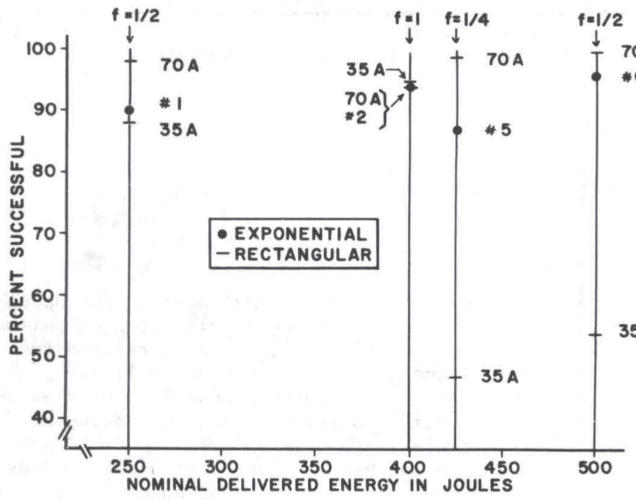

Figure 3. Percent success of ventricular defibrillation related to fractional undershoot and delivered energy for bidirectional truncated exponential waveforms in which leading half-cycle current sweeps from 70 to 35 amp and for bidirectional rectangular waveforms in which the leading half-cycle is either 70 or 35 amps.

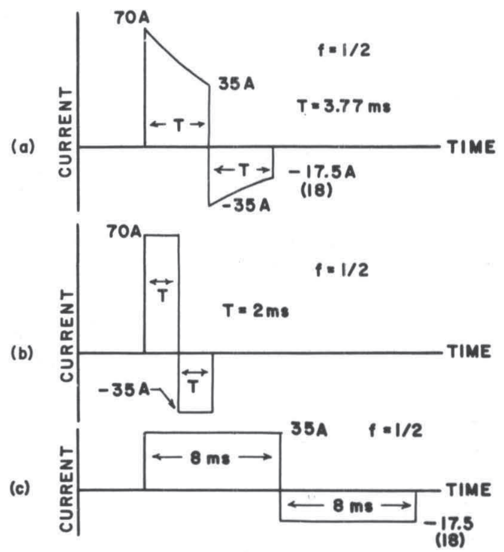

Figure 2. Waveforms which have the same value of undershoot and which deliver the same energy to a given load. (a) First bidirectional truncated exponential waveform evaluated. (b) Bidirectional rectangular waveform having current amplitude of leading half-cycle equal to the initial current value of leading half-cycle of exponential waveform. (c) Bidirectional rectangular waveform having current amplitude of leading half-cycle equal to final value of current in leading half-cycle of exponential waveform.

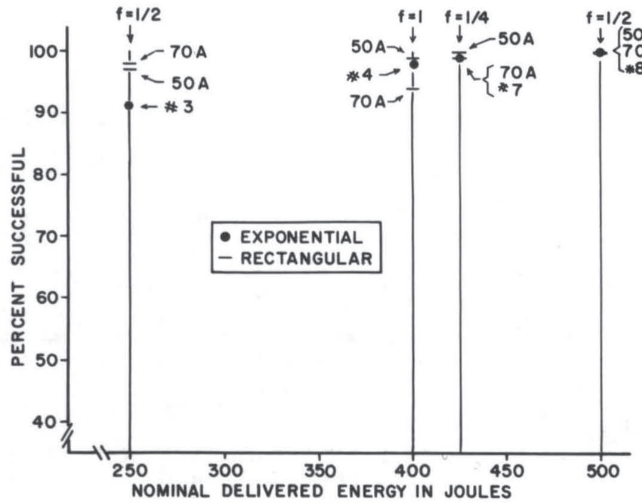

Figure 4. Percent success of ventricular defibrillation related to fractional undershoot and delivered energy for bidirectional truncated exponential waveforms in which leading half-cycle current sweeps from 70 to 50 amps and for bidirectional rectangular waveforms in which the leading half-cycle is either 70 or 50 amps.

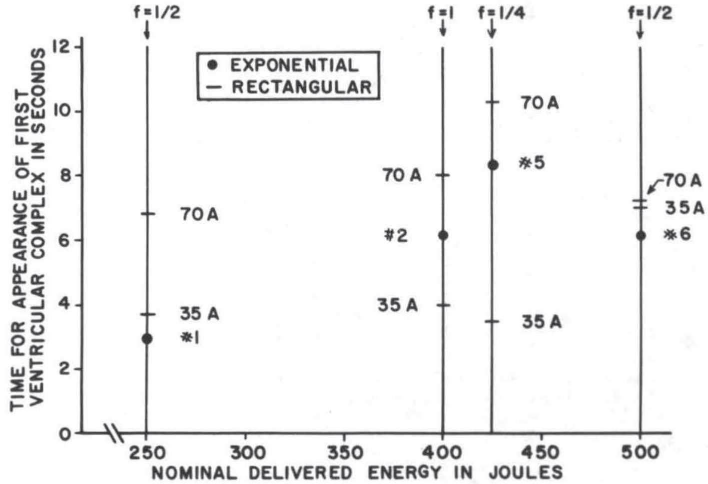

Figure 5. Mean time required for appearance of first ventricular complex following a defibrillatory shock related to fractional undershoot and delivered energy for bidirectional truncated exponential waveforms in which leading half-cycle current sweeps from 70 to 35 amps and for bidirectional rectangular waveforms in which the leading half-cycle is either 70 or 35 amps.

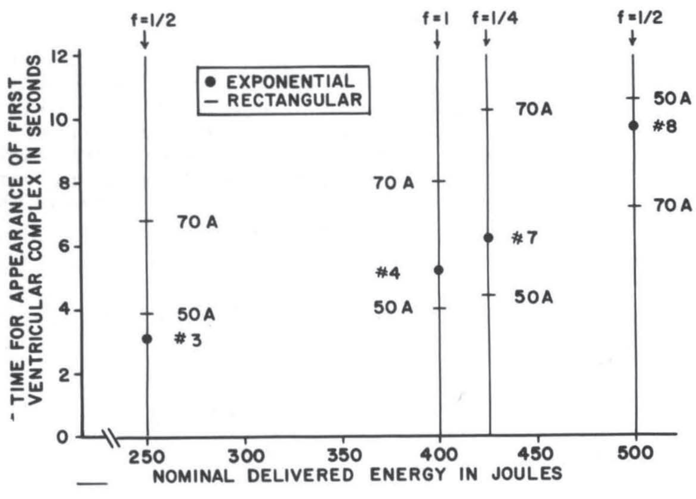

Figure 6. Mean time required for appearance of first ventricular complex following a defibrillatory shock related to fractional undershoot and delivered energy for bidirectional truncated exponential waveforms in which leading half-cycle current sweeps from 70 to 50 amps and for bidirectional rectangular waveforms in which the leading half-cycle is either 70 or 50 amps.

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.