JACC Vol. 14, No. 1
July 1989:242–5

Comparison of Monophasic With Single and Dual Capacitor Biphasic Waveforms for Nonthoracotomy Canine Internal Defibrillation

PETER D. CHAPMAN, MD, FACC, JAMES W. VETTER, MD, JOSEPH J. SOUZA, MS, JULE N. WETHERBEE, MD, PAUL J. TROUP, MD, FACC

Milwaukee, Wisconsin

Monophasic and single capacitor and dual capacitor biphasic truncated exponential shocks were tested in pentobarbital-anesthetized dogs with use of a nonthoracotomy internal defibrillation pathway consisting of a right ventricular catheter electrode and a subcutaneous chest wall patch electrode. Seven dogs weighing 20.2 ± 0.5 kg were utilized. Monophasic pulses of 10 ms duration were compared with three biphasic pulses. All biphasic waveforms had an initial positive phase (P_1) followed by a terminal negative phase (P_2) and the total duration of P_1 plus P_2 was 10 ms. The dual capacitor biphasic waveform (P_1 9 ms, P_2 1 ms) had equal initial voltages of P_1 and P_2. Two simulated single capacitor biphasic waveforms were also tested, the first designed to minimize the magnitude of P_2 (P_1 9 ms, P_2 1 ms with initial voltage of P_2 equal to 0.3 of the initial voltage of P_1) and the second to maximize P_2 (P_1 5 ms, P_2 5 ms with initial voltage of $P_2 = 0.5\ P_1$).

Alternating current was used to induce ventricular fibrillation and four trials of eight initial voltages from 100 to 800 V were performed for each of the four waveforms. Stepwise logistic regression was utilized to construct curves relating probability of successful defibrillation and energy.

In the logistic model, the dual capacitor biphasic and single capacitor biphasic waveforms that maximized P_2 were associated with significantly ($p < 0.001$) lower energy requirements for defibrillation than those of the monophasic waveform. The single capacitor biphasic waveform that minimized P_2 was not significantly better than the monophasic waveform. The biphasic waveforms associated with the lowest energy requirements for defibrillation were characterized by a higher P_2/P_1 energy ratio.

These results demonstrate that single capacitor biphasic waveforms can be constructed that are superior to similar duration monophasic waveforms and comparable with some dual capacitor biphasic waveforms. The relative magnitude of P_1 and P_2 appears to be an important determinant of defibrillation efficacy.

(J Am Coll Cardiol 1989;14:242–5)

Appropriately configured biphasic truncated exponential waveforms have been shown to significantly lower energy requirements for defibrillation compared with monophasic truncated exponential waveforms using a variety of electrode systems (1–5). Favorable biphasic waveforms have been characterized by initial phase greater than or equal in duration to the trailing phase of opposite polarity (3,4). We have reported (4) a significant decrease in energy requirements for nonthoracotomy canine internal defibrillation using two capacitor biphasic waveforms (initial positive phase; trailing negative phase, with leading edge voltage equal for each phase) compared with monophasic waveforms of the same total duration. Single capacitor biphasic waveforms might permit greater flexibility in implanted device design and additionally, at short pulse durations, single capacitor devices would improve the ratio of delivered to stored energy. A fundamental limitation of a single capacitor biphasic waveform is that the trailing edge voltage of the initial phase is the maximal possible leading edge voltage of the second phase and is dependent on the initial voltage and the tilt of the initial phase.

The present experiment was performed 1) to compare the relative efficacy of single and dual capacitor biphasic waveforms with that of monophasic shocks by using a nonthoracotomy implanted defibrillation pathway, and 2) to determine if the magnitude of the second phase of the single capacitor biphasic waveform is an important determinant of defibrillation efficacy.

From the Medical College of Wisconsin, Division of Cardiology, Department of Medicine, Milwaukee, Wisconsin.

Manuscript received September 19, 1988; revised manuscript received December 1, 1988, accepted January 6, 1989.

Address for reprints: Peter D. Chapman, MD, Division of Cardiology, Medical College of Wisconsin, 8700 West Wisconsin Avenue, Milwaukee, Wisconsin 53226.

0735-1097/89/$3.50

Methods

Experimental preparation. We (6) have previously described the experimental preparation in detail. Seven mongrel dogs weighing 20.2 ± 0.5 kg (mean ± 1 SD) were anesthetized with intravenous pentobarbital, intubated and ventilated with a volume respirator using room air. The left femoral artery was cannulated to sample arterial blood every 30 min and to continuously monitor arterial pressure. The respirator was adjusted to maintain the partial pressure of oxygen (po_2) > 80 mm Hg, the partial pressure of carbon dioxide (pco_2) between 25 and 45 mm Hg and the pH between 7.35 and 7.45. The studies conformed to the "Position of the American Heart Association on Research Animal Use" adopted November 11, 1984.

An 11F transvenous cardioverter-defibrillator catheter (CPI, Inc.) was placed through the right external jugular vein into the right ventricular apex under fluoroscopic guidance. The catheter has a 16 mm^2 tip electrode used for pacing and delivery of alternating current, a 4 cm^2 titanium distal electrode located 4 mm from the tip that was used as the cathode for defibrillation and an 8 cm^2 titanium proximal electrode that was not used. A pacing threshold of <1.0 V (1 ms pulse width) was required for satisfactory catheter position. A 13.9 cm^2 titanium patch electrode (CPI, Inc.) was placed subcutaneously over the point of maximal cardiac impulse and served as the anode for defibrillation.

Fibrillation-defibrillation trials. Ventricular fibrillation was induced with brief application of 60 Hz alternating current to the tip-distal electrode bipole, and was allowed to continue for 10 s before internal defibrillation was attempted. All failed defibrillation attempts were followed by a transthoracic rescue shock of known efficacy such that only one internal shock was assessed for each fibrillation episode. Consecutive fibrillation trials were separated by at least 1.5 min.

The microprocessor-based external defibrillator used for the experiment (Ventritex HVS-02) digitally displays delivered energy and lead impedance for each shock. The device has an effective capacitance of 150 μF on each of two defibrillation output circuits (pulse 1 or P_1 and pulse 2 or P_2) and can deliver one (P_1 alone) or two (P_1 plus P_2) truncated exponential shocks. P_1 and P_2 are independently programmable with respect to leading edge (initial) voltage, pulse width and interpulse delay. P_1 polarity is constrained as positive, whereas P_2 polarity may be programmed positive or negative. Monophasic pulses were constructed with use of P_1 alone. Biphasic pulses utilized a positive polarity P_1 followed by a negative polarity P_2. Interpulse delay was set at 0 ms but was 0.25 ms because of the switch time constant.

Waveforms used for defibrillation. Four pulse configurations were tested in this experiment (Fig. 1). The total pulse duration for all shocks was 10 ms. Monophasic shocks were compared with three different biphasic waveforms: a dual capacitor biphasic waveform (P_1 duration 9 ms, P_2 1 ms with the initial voltage equal for P_1 and P_2), and two simulated single capacitor biphasic waveforms (one designed to minimize and the other to maximize the energy content or magnitude of P_2).

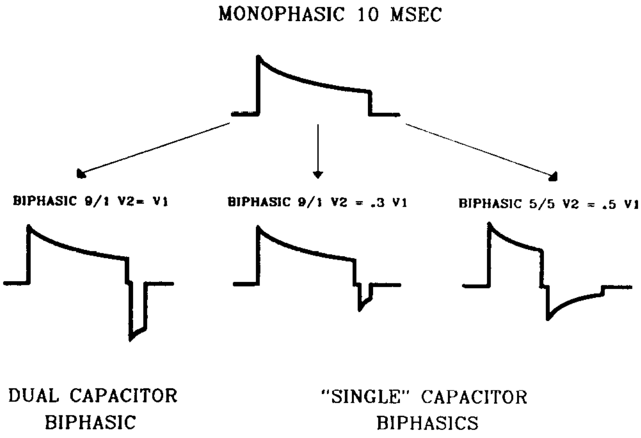

Figure 1. The four waveforms tested are shown. All have a total pulse width of 10 ms. The dual capacitor biphasic waveform has an initial positive phase (P_1) of 9 ms and a terminal negative phase (P_2) of 1 ms (9/1). The initial voltage of the second phase (V_2) is the same as the initial voltage of the first phase (V_1). The two simulated single capacitor biphasic waveforms are shown. The first has the same phase durations (9/1) as the dual capacitor biphasic waveform with V_2 = 0.3 V_1 and minimizes the energy magnitude of the second phase (P_2). The second biphasic waveform has phase durations of 5 ms each (5/5) with V_2 = 0.5 V_1 (maximizing the energy magnitude of the second phase). See text for discussion.

The simulated single capacitor biphasic shocks were constructed to utilize the trailing edge voltage of the initial pulse as the leading edge voltage of the terminal negative phase. The trailing edge voltage (V_f) of the initial phase can be estimated given the leading edge (V_i) voltage, the duration of the pulse (d), the capacitance (C) and the impedance (R) using the equation $V_f = V_i - V_i[1 - e^{(-d/RC)}]$. The pulse duration and initial voltage are set and the effective capacitance is known; therefore, the only unknown is the impedance. From extensive prior experience with the lead system and external defibrillator, an impedance value of approximately 60 Ω was anticipated (7). Therefore, the calculations of V_f were made with use of this value. This procedure resulted in values of 0.37 V_i and 0.57 V_i for the simulated single capacitor waveforms that minimized and maximized P_2 magnitude. These values were rounded to 0.3 V_i and 0.5 V_i, respectively, to ensure that unexpectedly low impedance values would not result in the P_2 voltage setting being >100% of the V_f of P_1. Therefore only impedance values of <50 Ω would result in less voltage available from a true single capacitor than was set using the two capacitors to simulate a single capacitor.

Experimental protocol and statistical analysis. Four trials at eight initial voltages from 100 to 800 V in 100 V increments

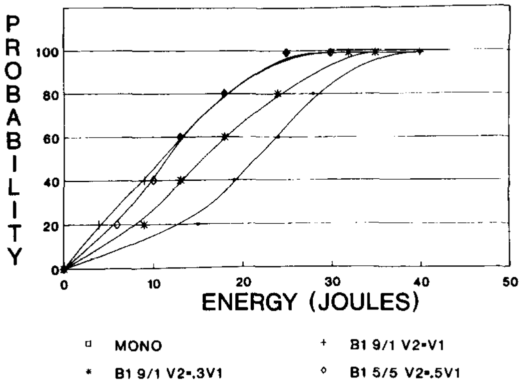

Figure 2. The curves relating energy in joules and probability of successful defibrillation in percent are shown for the four waveforms tested. See text for discussion. B = biphasic; MONO = monophasic; other abbreviations as in Figure 1.

Table 1. Summary of Waveform Variables

		Biphasic		
	Mono	A	B	C
E_{80}	28	18*	24	18*
V_{80}	650	470*	590*	510*
d/s	0.88	0.54	0.92	0.92
P_2/P_1	—	0.23	0.03	0.32

*$p < 0.001$ compared with monophasic. Biphasic A = dual capacitor biphasic (first phase 9 ms, second phase 1 ms, initial voltage equal for each phase); Biphasic B = simulated single capacitor biphasic with the same durations as A but having an initial voltage of the second phase (P_2) set at 0.3 times the initial voltage of the first phase (P_1); Biphasic C = simulated single capacitor biphasic, each phase 5 ms with the initial voltage of the second phase equal to 0.5 times the initial voltage of the first phase; d/s = ratio of delivered to stored energy calculated at E_{80} for the group of animals; E_{80} = energy in joules delivered at 80% probability of defibrillation from the group logit curve; Mono = monophasic; V_{80} = preset initial voltage in volts of the monophasic waveform or the first phase of the biphasic waveform at 80% probability of defibrillation from the group logit curve; P_2/P_1 = ratio of the energy contents of the second to the first phase of the biphasic waveforms calculated at E_{80} for the group as a whole. See text for discussion.

were performed for each of the four pulse configurations. For each dog there was a total of 128 fibrillation-defibrillation episodes. The order of shocks was determined randomly. For each trial the delivered energy and impedance values were recorded along with the success or failure of the test shock. A logit dose-response curve was fit for each of the four waveforms, combining data from all of the dogs studied. Comparison of the four logit curves was performed with logistic regression analysis (8), which examined the influence of waveform on defibrillation efficacy. In addition a goodness of fit chi-square is generated, which tests the hypothesis that the logistic model fits the data adequately. For all analyses a p value <0.05 was considered significant. The mean lead system impedance was also calculated for the experiment.

Results

The measured impedance during the experiment was 59 ± 5 Ω; therefore, the simulated single capacitor calculations based on an assumed impedance of 60 Ω were deemed appropriate.

Relation of waveform to defibrillation efficacy. The curves relating probability of successful defibrillation and delivered energy for the four pulse configurations are shown in Figure 2. In the logistic model, pulse configuration was a highly significant determinant of defibrillation efficacy. The p value for the goodness of fit chi-square was 0.008, indicating that the logistic model fit the data adequately. The dual capacitor biphasic waveform and the simulated single capacitor biphasic waveform that maximized the magnitude of pulse 2 (P_2) were associated with significantly ($p < 0.001$) lower energy requirements for defibrillation than was the monophasic waveform. The simulated single capacitor biphasic waveform that minimized the magnitude of the second pulse (P_2) was not associated with significantly lower defibrillation energy requirements when compared with the monophasic waveform. All three biphasic waveforms were associated with significantly ($p < 0.001$) lower voltage requirements for defibrillation than those of the monophasic waveform.

From the fitted group data the voltages and energies associated with 80% probability of successful defibrillation and the delivered/stored energy ratios are shown in Table 1. The delivered/stored energy ratio was highest for the simulated single capacitor waveforms (which utilized the trailing edge voltage of the first phase as the leading edge voltage of the second phase), slightly lower for the monophasic waveform and lowest for the dual capacitor biphasic waveform (reflecting greater energy waste).

Relation of magnitude of the second phase (P_2) of the biphasic waveforms and efficacy. The biphasic waveforms associated with the lowest energy requirements for defibrillation were characterized by having a higher ratio of energy in the second or negative phase as compared with the first phase. The dual capacitor biphasic (A) and the simulated single capacitor waveform that maximized the energy content of the second phase (C) had energy ratios of the second to the first phase of 0.23 and 0.32, respectively (Table 1). The simulated single capacitor biphasic waveform that minimized the energy of the second phase (B) was not associated with lower energy requirements for defibrillation than those of the monophasic waveform and had the lowest ratios of energy content of the second phase to the first phase of 0.03.

Discussion

Biphasic waveform configuration and defibrillation efficacy. Biphasic waveforms demonstrating improved defibrillation efficacy compared with monophasic waveforms are characterized by initial phases whose duration is greater than or equal to that of the second phase of opposite polarity. In contrast, biphasic waveforms with initial phases shorter in duration than the second phase have been associated with *higher* defibrillation energy requirements than corresponding monophasic waveform (3,4).

Given the appropriate relative durations of the two phases of the biphasic waveform, the relative magnitude (energy content) of the two phases also appears to be an important determinant of defibrillation efficacy. The present experiments demonstrate improved efficacy of the biphasic waveforms with second pulse to first pulse (P_2/P_1) energy ratios of 0.23 and 0.32, whereas the simulated single capacitor waveform that minimized P_2 magnitude and had a P_2/P_1 energy ratio of 0.03 failed to demonstrate improved efficacy compared with the monophasic waveform.

In addition to being "too small" in energy content, the second phase can apparently also be too large. Dixon et al. (3) noted that a biphasic waveform with a P_2/P_1 energy ratio >1.0 was no more effective than the corresponding monophasic waveform. This finding is also consistent with the work of Jones and Jones (8), who noted less postshock cellular dysfunction in cultured myocardial cells with biphasic waveforms characterized by low amplitude second phases and potentiation of cellular dysfunction with high amplitude second phases.

The mechanism of improved efficacy for appropriately configured biphasic shocks requires further definition, but may relate to improved cellular excitation, prevention of refibrillation or other factors. In addition to describing the amelioration of postshock cellular dysfunction by some biphasic waveforms that may relate to a decreased propensity for refibrillation, Jones et al. (9) reported reduced excitation thresholds for biphasic as compared with monophasic rectangular waveforms in cultured myocardial cells. They suggested that the first phase acts to sensitize the cell to excitation by the second phase.

Daubert et al. (10) recently reported that biphasic shocks despite having improved defibrillation efficacy are less able than are monophasic shocks to excite partially refractory myocardium as assessed by multielectrode mapping in the canine heart. They suggest that factors other than excitation of tissue, such as prevention of refibrillation, are important.

Single versus dual capacitor biphasic waveforms. The present experiment demonstrates that single capacitor variable tilt truncated exponential biphasic waveform shocks can be constructed that are superior to similar duration monophasic waveforms and comparable with some dual capacitor biphasic waveforms. Additionally, the single capacitor pulses result in improved ratios of delivered to stored energy. Because implanted defibrillator size and design are to a large extent constrained by capacitor and battery size, single capacitor devices would provide greater flexibility for implanted device design and offer great promise for the development of small nonthoracotomy defibrillation systems for clinical use. Further work will be necessary to define the optimal P_2/P_1 energy ratio within the constraints of a single capacitor system that limits P_2 initial voltage to the trailing edge voltage of P_1. Additionally, the optimal variables for the biphasic waveform may relate in part to the lead system used, whether or not a fixed duration waveform is utilized and the effective capacitance. These variables were not addressed by the present study.

We thank Tammy Jo Wells for preparation of the manuscript.

References

1. Schuder JC, Stoeckle MD, Dolan AM. Transthoracic ventricular defibrillation with square-wave stimuli: one-half cycle, one cycle, and multicycle waveforms. Circ Res 1964;15:258–64.
2. Shuder JC, Gold JH, Stoeckle H, Roberts SA, McDaniel WC, Moellinger DW. Defibrillation in the calf with bidirectional trapezoidal wave shocks applied via chronically implanted epicardial electrodes. Trans Am Soc Artif Intern Organs 1981;37:467–70.
3. Dixon EG, Tang ASL, Wolf PD, et al. Improved defibrillation thresholds with large contoured epicardial electrodes and biphasic waveforms. Circulation 1987;76:1176–84.
4. Chapman PD, Vetter JW, Souza JJ, Troup PJ, Wetherbee JN, Hoffmann RG. Comparative efficacy of monophasic and biphasic truncated exponential shocks for nonthoracotomy internal defibrillation in dogs. J Am Coll Cardiol 1988;12:739–45.
5. Fain ES, Sweeney MB, Franz MR. Improved internal defibrillation efficacy using a biphasic waveform (abstr). Circulation 1987;76(suppl IV):IV-312.
6. Wetherbee JN, Chapman PD, Klopfenstein HS, Bach SM, Troup PJ. Nonthoracotomy internal defibrillation in dogs: threshold reduction using a subcutaneous chest wall electrode with a transvenous catheter electrode. J Am Coll Cardiol 1987;10:406–11.
7. Chapman PD, Wetherbee JN, Vetter JW, Troup PJ, Souza P. Strength-duration curves of fixed pulse width variable tilt truncated exponential waveforms for nonthoracotomy internal defibrillation in dogs. PACE 1988:11:1045–50.
8. Jones JL, Jones RE. Decreased defibrillator-induced dysfunction with biphasic rectangular waveforms. Am J Physiol 1984;247:H792–6.
9. Jones JL, Jones RE, Balasky G. Improved cardiac cell excitation with symmetrical biphasic defibrillator waveforms. Am J Physiol 1987; 253:H1418–24.
10. Daubert JP, Frazier DW, Tang ASL, Hagler JA, Smith WM, Ideker RE. Biphasic shocks excite refractory myocardium less effectively than monophasic shocks (abstr). PACE 1988;11:503.