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Triphasic Waveforms Are Superior to Biphasic Waveforms for Transthoracic Defibrillation

Experimental Studies

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OBJECTIVES Our objective was to evaluate the efficacy of triphasic waveforms for transthoracic defibrillation in a swine model.

BACKGROUND Triphasic shocks have been found to cause less post-shock dysfunction than biphasic shocks in chick embryo studies.

METHODS After 30 s of electrically induced ventricular fibrillation (VF), each pig in part I (n = 32) received truncated exponential biphasic (7.2/7.2 ms) and triphasic (4.8/4.8/4.8 ms) transthoracic shocks. Each pig in part II (n = 14) received biphasic (5/5 ms) and triphasic shocks (5/5/5 ms). Three selected energy levels (50, 100, and 150 J) were tested for parts I and II. Pigs in part III (n = 13) received biphasic (5/5 ms) and triphasic (5/5/5 ms) shocks at a higher energy (200 and 300 J). Although the individual pulse durations of these shocks were equal, the energy of each pulse varied. Nine pigs in part I also received shocks where each individual pulse contained equal energy but was of a different duration (biphasic 3.3/11.1 ms; triphasic 2.0/3.2/9.2 ms).

RESULTS Triphasic shocks of equal duration pulses achieved higher success than biphasic shocks at delivered low energies: <40 J: 38 ± 5% triphasic vs. 19 ± 4% biphasic ($p < 0.01$); 40 to <50 J: 66 ± 7% vs. 42 ± 7% ($p < 0.01$); and 50 to <65 J: 78 ± 4% vs. 54 ± 5% ($p < 0.05$). Shocks of equal energy but different duration pulses achieved relatively poor success for both triphasic and biphasic waveforms. Shock-induced ventricular tachycardia (VT) and asystole occurred less often after triphasic shocks.

CONCLUSIONS Triphasic transthoracic shocks composed of equal duration pulses were superior to biphasic shocks for VF termination at low energies and caused less VT and asystole. (J Am Coll Cardiol 2003;42:568–75) © 2003 by the American College of Cardiology Foundation

Biphasic waveform shocks are superior to monophasic shocks for the termination of ventricular fibrillation (VF) (1–3). Biphasic waveforms improve defibrillation efficacy by two possible separate mechanisms: reduction of the defibrillation threshold and amelioration of shock-induced dysfunction (4–7).

Triphasic waveforms, composed of three pulses with the polarity of the second pulse reversed (i.e., positive, negative, and positive) have been evaluated. Jones and Jones (8) reported a high safety factor for triphasic waveforms. In their study, the authors postulated that the first pulse of a triphasic waveform acted as a "conditioning pre-pulse," the second pulse as an "exciting" or "defibrillating" pulse, and the third pulse as a "healing post-pulse," which ameliorated dysfunction caused by the first two pulses (8).

Only limited data are available on the effectiveness of triphasic truncated exponential waveforms in vivo, and most of these data are from internal defibrillation studies (9–11). Huang et al. (11) demonstrated that at least some versions of triphasic waveforms were superior to biphasic waveforms; phase durations and electrode polarity seemed important in determining triphasic shock efficacy. Kidwai et al. (12) studied a rounded variant of triphasic waveforms and could not demonstrate their superiority for transthoracic defibrillation.

Our objective was to compare the effectiveness and safety of transthoracic triphasic versus biphasic truncated exponential waveform shocks. We evaluated two types of triphasic shocks: equal duration/different energy pulses and equal energy/different duration pulses and compared them with similarly constructed biphasic shocks.

METHODS

Animal preparation. The study was approved by the University of Iowa Animal Care and Use Committee. Pigs weighing 18 to 28 kg were anesthetized with a mixture of intramuscular ketamine and acepromazine (20 mg to 0.2 mg/kg), with sodium pentobarbital (50 mg/ml intravenously) supplementation. A volume-cycled respirator was used to maintain arterial pH (7.35 to 7.45) and inspired oxygen fraction was adjusted to maintained partial pressure

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Abbreviations and Acronyms

CI = confidence interval
GEE = generalized estimating equations
LVEDP = left ventricular end-diastolic pressure
OR = odds ratio
PEA = pulseless electrical activity
VF = ventricular fibrillation
VT = ventricular tachycardia

of oxygen >100 mm Hg. Heparin was administered. Cardiac output was measured by thermodilution.

VF and ventricular defibrillation. Ventricular fibrillation was initiated electrically by the passage of a 60-Hz alternating current through a catheter to the right ventricular apex. Defibrillating shocks were delivered from a custom-built defibrillator with a 115-μF capacitor, which was capable of delivering biphasic or triphasic truncated exponential waveform shocks with polarity, pulse duration, and selected energy, as determined by the operator. The tilt of each pulse was determined by the relationship: tilt = 1 − exp (−t/R·C), where exp = natural exponent; t = discharge time; R = discharge impedance; and C = capacitance.

To raise the total transthoracic impedance to levels comparable to the average human impedance, resistors of varying impedance (25, 50, and/or 75 ohm) were placed between the defibrillator and electrodes. We gave an initial single "test" shock (without inducing VF) to determine transthoracic impedance and then added the appropriate resistor to bring the total impedance of the system (animal plus resistor) to 75 to 80 ohm, approximating the typical human transthoracic impedance (13). The four shock types (biphasic equal-duration pulses, biphasic equal-energy pulses, triphasic equal-duration pulses, triphasic equal-energy pulses) were initially administered in a random sequence. It soon became clear, however, that the success rate of the equal-energy pulse shocks was poor (i.e., those shocks frequently failed to terminate VF). After six pigs were studied, to avoid an excessive number of high-energy "rescue" shocks and experimental deterioration, we then changed the order of shock administration to begin either with triphasic or biphasic equal-duration pulse waveforms. The defibrillation shocks were delivered from commercially available self-adhesive monitor-defibrillator electrode pads (model M3501A, Philips Medical Systems, Andover, Massachusetts) with a conductive area of 102 cm^2, placed on the shaved chest of the pig. One pad was placed anteriorly over the sternum, and the second pad was placed posteriorly over the vertebral column.

We performed a study consisting of three different parts.

Part I. Truncated exponential triphasic and biphasic shocks (total duration of 14.4 ms) were administered to 32 pigs. There were two types of biphasic/triphasic waveforms: individual pulses of equal duration (but varying energy) and individual pulses of equal energy (but varying duration). The biphasic waveform shocks composed of equal-duration pulses included a positive pulse (7.2 ms) and a negative pulse (7.2 ms). The biphasic equal-energy pulse shocks consisted of a positive 3.3-ms and negative 11.1-ms pulse. For the triphasic waveform shocks, the equal-duration pulse waveform was composed of a positive pulse (4.8 ms), a negative pulse (4.8 ms), and a positive pulse (4.8 ms). The triphasic equal-energy pulse waveform consisted of three pulses of durations of 2.0, 3.2, and 9.2 ms. The equal-energy pulse durations were determined assuming a discharge impedance of 90 ohm (based on the fixed 115-μF defibrillator capacitor). An impedance of 90 ohm was required to achieve a minimum pulse duration of 2 ms. (With a truncated exponential waveform, energy is delivered more rapidly earlier in the waveform. Thus, the first pulse is the shortest.)

For the first phases of both triphasic and biphasic shocks, the sternum (anterior) electrode was positive (anode) and the vertebral (posterior) electrode was negative (cathode). This was reversed during the second pulses of both biphasic and triphasic shocks: the posterior electrode was positive (anode) and the anterior electrode was negative (cathode). The third pulse of the triphasic shock was similar to the first pulse.

Because the actual impedance varied from 90 ohm, the actual energy distributions of the triphasic "equal"-energy pulse waveforms differed slightly from equality. At 78 ohm (the mean impedance of all shocks), the triphasic energy distributions were 37%, 34%, and 29%. The corresponding distributions for the biphasic equal-energy pulses were 53% and 47%. The waveform tilts varied with impedance: for the entire group, the overall tilts of the biphasic shocks were 79% (50 J), 79% (100 J), and 81% (150 J); for the triphasic shocks, the tilts were 80% (50 J), 80% (100 J), and 80% (150 J). Examples of biphasic and triphasic equal-duration and equal-energy shocks are shown in Figure 1. Shocks at selected energy levels of 50, 100, and 150 J were administered in random order.

Part II. Fourteen pigs were included in the part II study. All pigs in part II received equal-duration pulse biphasic (5/5 ms) and triphasic shocks (5/5/5 ms) at selected energies of 50, 100, and 150 J, in random order, to compare the efficacy of two waveforms where the individual pulses were of equal duration (5 ms), but the total durations of the shock varied by 50%.

Part III. Thirteen pigs were included in the part III study. Each pig received, in random order, equal-duration pulse biphasic (5/5 ms) and triphasic shocks (5/5/5 ms) at selected high energies only: 200 and 300 J. This was done to see whether triphasic shock success could reach 100% at selected high energies.

Protocol. MEASUREMENTS. Ventricular fibrillation was induced and allowed to persist for 30 s. To terminate VF, four shocks of each waveform were administered sequentially at each of the three energy levels tested. The results were then averaged to yield a percent success rate at each energy level for each waveform in that animal (i.e., each data point

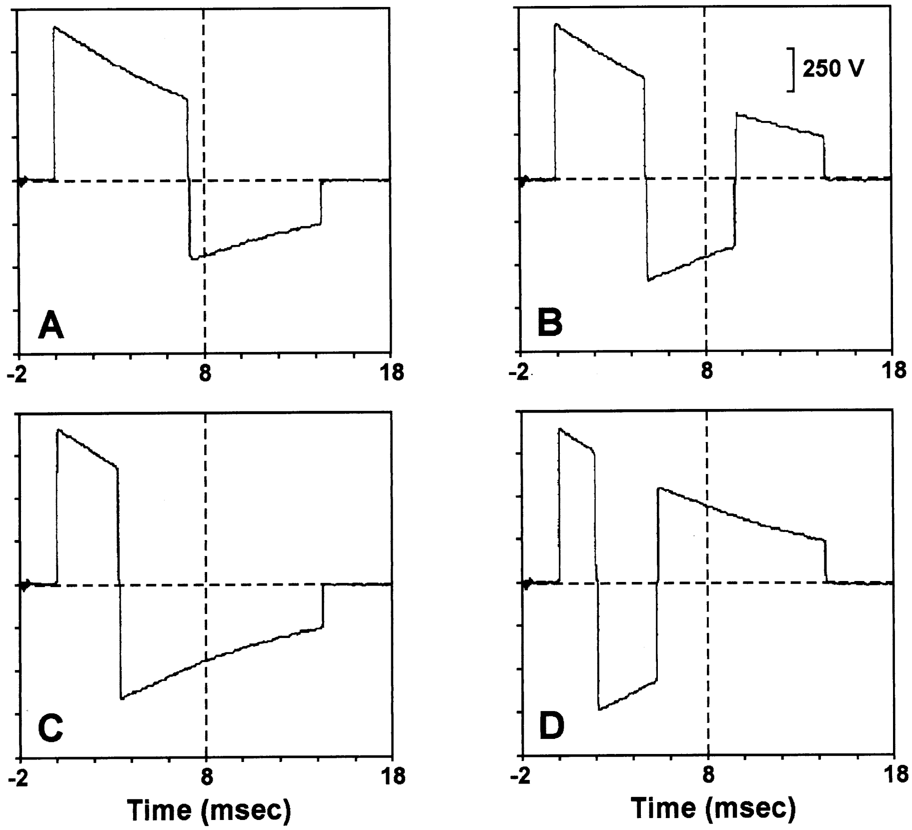

Figure 1. Examples of biphasic and triphasic waveforms: biphasic equal-duration pulses **(A)**, triphasic equal-duration pulses **(B)**, biphasic equal-energy pulses **(C),** and triphasic equal-energy pulses **(D)**.

represents the percent success of the four shocks at that energy level for that waveform). We did not combine different waveforms. Success was defined as termination of VF 5 s after the shock, regardless of the resultant rhythm, including sinus rhythm, ventricular asystole, and pulseless electrical activity (PEA). Energy level versus success curves were constructed. If a shock failed to defibrillate, 200 J and, if necessary, higher "rescue" shocks were given. Data from rescue shocks were excluded from percent success calculations. If asystole or PEA persisted for >5 s after any shock, external manual closed-chest massage was initiated until a perfusing rhythm was restored.

In part I, at 1 min after each shock, left ventricular end-diastolic pressure (LVEDP), arterial blood pressure, and the occurrence of any electrocardiographic ST-segment elevation were recorded to determine post-shock myocardial damage. Cardiac output was repeated at the end of four shocks at each energy level. Ventricular tachycardia (VT) (lasting >5 s) and cardiac asystole or PEA (lasting >5 s) after any shock, or at any time before the next shock, were noted.

Leading-edge and trailing-edge transthoracic impedances (animal plus fixed resistor) and currents were displayed on the defibrillator after each shock.

The actually delivered energy was calculated as follows: Animal impedance = total impedance − resistor impedance. Delivered energy = (animal impedance/total impedance) × energy of the shock delivered to the entire system.

Statistical analysis. The energy actually delivered to the animals receiving equal-duration pulse shocks was divided into five intervals, obtained from the distribution of delivered energy values, such that there were a similar number of points within each interval (i.e., cut-points were close to the 20th, 40th, 60th, and 80th percentiles of the distribution of delivered energy). For consistency, the same intervals were used for parts I, II, and III. The intervals for delivered energy were ≤40 J, 40 to <50 J, 50 to <65 J, 65 to <90 J, and ≥90 J. The data were from the results of the equal-duration pulse study involving all animals in parts I, II, and III. The mean number of equal-duration pulse shocks/animal in part I was 23; in part II, it was 29; and in part III, it was 25.

Due to the smaller sample number for part I pigs receiving equal-energy pulse shocks (n = 9), the energy actually delivered to the animals in this group was divided into only three intervals. The intervals for delivered energy were ≤40 J, 40 to <65 J, and ≥65 J. The mean number of equal energy pulse shocks/animal was 20.

Success of VF termination was compared between biphasic and triphasic shocks of equal-duration pulses adjusting for actual delivered energy (as categorized earlier) using

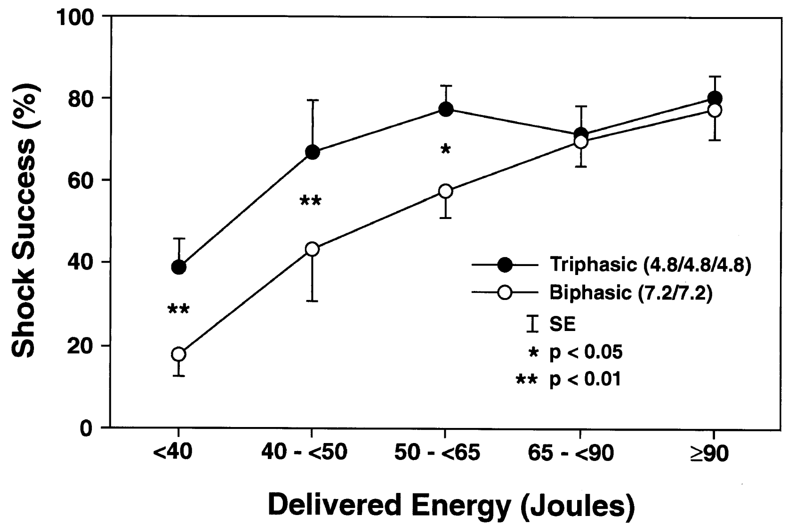

Figure 2. Shock success of triphasic (4.8/4.8/4.8 ms) and biphasic (7.2/7.2 ms) waveform shocks of equal-duration pulses at five intervals of actually delivered energy to the animals in part I. Triphasic waveform shocks achieved higher success rates at the intervals of ≤40 J, 40 to <50 J, and 50 to <65 J (n = 32).

logistic regression analysis with the generalized estimating equations (GEE) method (14). The dependent variable in the logistic regression model was success/failure of VF determination, and the independent variables were waveform, actual delivered energy, and the interaction of waveform-delivered energy. The GEE method was used in this analysis to account for the correlation between responses from the same animal, as there were multiple observations from the same animal for each waveform and various delivered energies. From this logistic regression analysis, the odds ratio (OR) of shock success of the triphasic waveform relative to biphasic waveform was computed (with 95% confidence intervals [CI] and p values) for each interval of delivered energy. This analysis was performed using SAS/STAT (SAS version 8.2, SAS Institute, Inc., Cary, North Carolina) procedure GENMOD, with the REPEATED statement to invoke the GEE method (14).

The leading-edge and trailing-edge impedances, mean current, and leading-edge and trailing-edge currents of the equal-duration pulse shocks were compared between biphasic and triphasic waveforms at selected levels of 50, 100, and 150 J (part I), using the Wilcoxon sign-rank test. For these comparisons, the average of the four measurements obtained from the four shocks given to each animal for each waveform at each energy level was used. Because the comparison of the waveforms was done at the three energy levels, the p values were adjusted using the Bonferroni method to account for the three tests. A Bonferroni-adjusted p value <0.05 was considered to be statistically significant.

For shock toxicity, the logistic regression analysis using the GEE method (14) was performed to compare the incidence of shock-induced VT, shock-induced asystole, and ST-segment elevation between biphasic and triphasic waveforms. This analysis only included successful shocks. The independent variables in the logistic regression model were waveform (biphasic vs. triphasic) and energy level (50, 100, and 150 J). The interaction between waveform and energy level was first included in the model, but was later removed because it was not significant. The test of comparing these events between waveforms was averaged across the three energy levels.

RESULTS

Comparison of shock success between biphasic and triphasic shocks of equal-duration pulses: part I. Triphasic waveform shocks of equal-duration pulses showed a significantly greater probability of shock success (termination of VF) at the delivered energy interval of ≤40 J ($p < 0.01$), with an OR of 2.95 (95% CI 1.78 to 4.90) for success of triphasic shocks relative to biphasic shocks (Fig. 2). This was also seen at the delivered energy interval of 40 to <50 J ($p < 0.01$; OR 2.68, 95% CI 1.28 to 5.62) and the delivered energy interval of 50 to <65 J ($p < 0.05$; OR 2.50, 95% CI 1.09 to 5.74). There were no significant differences in the success rate between triphasic and biphasic shocks at the delivered energy intervals of 65 to <90 J and ≥90 J (p = NS).

Shock success of equal-duration pulses: parts II and III. For brevity, the defibrillation results for parts II and III were summarized and combined in Figure 3 . Triphasic shocks demonstrated a significantly greater probability of defibrillation success compared with biphasic shocks at the delivered energy interval of 40 to <50 J ($p < 0.01$; OR 4.12, 95% CI 1.67 to 10.18) and 50 to <65 J ($p < 0.01$; OR 1.75, 95% CI 1.15 to 2.67) (Fig. 3). There was no significant difference in the success rate between triphasic and biphasic shocks at the delivered energy intervals of <40 J, 65 to <90 J, and ≥90 J (p = NS).

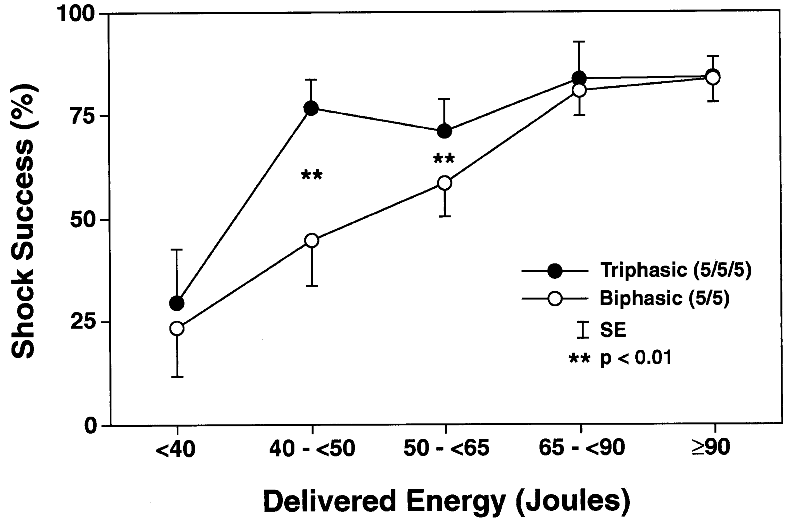

Figure 3. Shock success of triphasic (5/5/5 ms) and biphasic (5/5 ms) waveform shocks of equal-duration pulses at five intervals of actually delivered energy to the animals in parts II and III. Triphasic waveform shocks achieved higher success rates at the intervals of 40 to <50 J and 50 to <65 J (n = 27).

Comparison of shock success between biphasic and triphasic waveforms of equal-energy pulses (part I only). Shock success at the three delivered energy intervals was very low for biphasic equal-energy pulse shocks; for triphasic equal-energy pulse shocks, the success rate was low at <40 J and 40 to <65 J; at >65 J, success rose to 80% (Fig. 4). Triphasic shocks demonstrated a greater probability of defibrillation success compared with biphasic shocks at the delivered energy intervals of <40 J ($p < 0.05$; OR 5.93, 95% CI 1.01 to 34.71), 40 to <65 J ($p < 0.03$; OR 6.58, 95% CI 1.24 to 34.94), and ≥65 J ($p < 0.001$; OR 18.73, 95% CI 9.14 to 38.37).

Transthoracic impedance and currents of equal-duration pulse shocks. No significant differences in impedance or currents were seen in part I (Table 1). A comparison of mean current versus shock success showed that for currents of 6.0 and 8.4 amperes (A), generated by selected energy shocks of 50 and 100 J, triphasic waveform shocks achieved higher success than biphasic waveform shocks (Fig. 5).

Post-shock damage and hemodynamic data. The data were combined across the three energy levels for each waveform (Table 2).

Shock-induced VT occurred more often after successful biphasic waveform shocks than after successful triphasic waveform shocks ($p = 0.007$). The odds of shock-induced VT after biphasic shocks was 3.07 (95% CI 1.52 to 6.24) times the odds for triphasic shocks. The estimated probability of shock-induced VT was 0.23 (95% CI 0.15 to 0.32) for biphasic shocks and 0.09 (95% CI 0.05 to 0.16) for triphasic shocks.

Shock-induced asystole occurred more often after successful biphasic shocks than after successful triphasic shocks

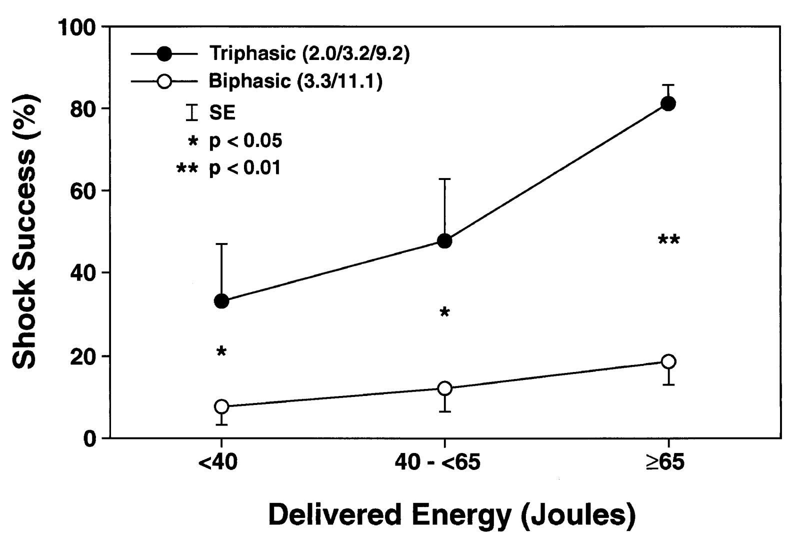

Figure 4. Shock success of triphasic (2.0/3.2/9.2 ms) and biphasic (3.3/11.1 ms) waveform shocks of equal-energy pulses at three intervals of actually delivered energy to the animals in part I. Triphasic waveform shocks achieved higher success rates at the intervals of ≤40 J, 40 to <65 J, and ≥65 J (n = 9).

Table 1. Transthoracic Impedance and Current

	50 J		100 J		150 J	
Selected Energy Waveform	**Bi**	**Tri**	**Bi**	**Tri**	**Bi**	**Tri**
Leading-edge impedance (ohm)	79 ± 3.4	78 ± 3.1	80 ± 2.9	78 ± 2.8	76 ± 2.9	76 ± 2.9
Trailing-edge impedance (ohm)	78 ± 2.8	76 ± 2.5	77 ± 2.5	76 ± 2.4	74 ± 2.4	75 ± 2.4
Leading-edge current (A)	12 ± 0.5	12 ± 0.5	17 ± 0.6	17 ± 0.6	21 ± 0.8	21 ± 0.8
Trailing-edge current (A)	2.3 ± 0.1	2.3 ± 0.1	3.2 ± 0.2	3.1 ± 0.1	3.8 ± 0.1	3.8 ± 0.1
Mean current (A)	5.9 ± 0.1	6.0 ± 0.1	8.4 ± 0.1	8.4 ± 0.1	10 ± 0.1	10 ± 0.1

Data from part I experiments are based on equal-duration pulse waveforms. Data are presented as the mean value ± SE.
Bi = biphasic waveform shocks; Tri = triphasic waveform shocks.

($p = 0.029$). The odds of shock-induced asystole after biphasic shocks was 2.63 (95% CI 1.23 to 5.63) times the odds for triphasic shocks. The estimated probability of shock-induced asystole was 0.17 (95% CI 0.10 to 0.26) for biphasic shocks and 0.07 (95% CI 0.04 to 0.14) for triphasic shocks.

ST-segment elevation after successful biphasic shocks tended to be higher than after triphasic shocks, but this difference was not statistically significant ($p = 0.074$). The odds of ST-segment elevation after biphasic shocks was 2.10 (95% CI 0.88 to 5.00) times the odds for triphasic shocks. The estimated probability of ST-segment elevation was 0.08 (95% CI 0.05 to 0.14) after biphasic shocks and 0.04 (95% CI 0.02 to 0.08) after triphasic shocks.

No differences in mean arterial pressure, LVEDP, and cardiac output were seen (Table 2). Also, no differences were seen between biphasic and triphasic shocks of equal-energy pulses (data not shown).

DISCUSSION

The main findings of this investigation were that transthoracic triphasic waveform shocks of equal-duration pulses were superior at low delivered energies to biphasic equal-duration pulse shocks for the termination of VF. Ventricular tachycardia and asystole were seen less often after equal-duration pulse triphasic shocks compared with biphasic shocks.

Mechanism of triphasic waveform superiority. What is the mechanism of triphasic waveform superiority for VF termination? Because the transthoracic impedances between biphasic and triphasic waveforms were similar, transthoracic impedance differences cannot explain the difference in shock success achieved by triphasic versus biphasic waveforms. Similarly, the observation that triphasic shocks achieved higher success rates at equal mean and leading-edge currents indicates that the waveform itself, not a higher electrical current passed through the heart, is responsible for the superiority of the triphasic waveform. Note, however, that we measured the transthoracic current but could not measure the trans*cardiac* current. As Lerman and Deale (15) showed that only a small proportion of total transthoracic current actually traverses the heart, we cannot entirely exclude the possibility that transcardiac current flow may differ between the triphasic and biphasic pathways, although this seems unlikely because the electrode positions remained constant throughout the experiments. The exact mechanism

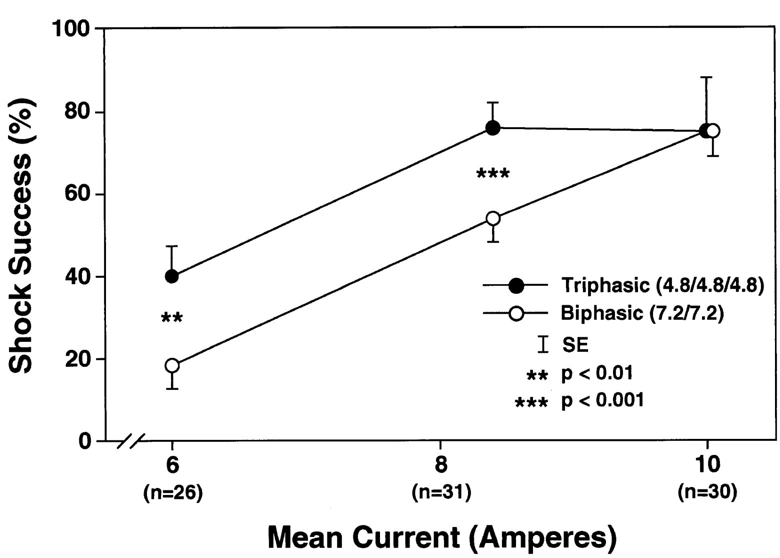

Figure 5. Mean current versus shock success of triphasic (4.8/4.8/4.8 ms) and biphasic (7.2/7.2 ms) waveform shocks of equal-duration pulses for all pigs in part I. Triphasic shocks with mean currents of 6 and 8.4 Amperes, generated by selected energy shocks of 50 and 100 J, achieved higher success than biphasic shocks (n = 32).

Table 2. Shock-Induced Toxicity

Selected Energy Waveform	50 J		100 J		150 J	
	Bi	Tri	Bi	Tri	Bi	Tri
Pre-shock LVEDP (mm Hg)	8.6 ± 0.5	8.4 ± 0.5	7.9 ± 0.4	7.6 ± 0.4	8.1 ± 0.5	8.1 ± 0.5
Post-shock LVEDP (mm Hg)	8.4 ± 0.7	8.0 ± 0.7	7.9 ± 0.5	7.4 ± 0.5	7.9 ± 0.5	7.7 ± 0.6
No. (%) of shocks causing ST-segment elevation >1 mV	3 (2.9)	0	5 (4.0)	3 (2.4)	10 (8.3)	8 (6.7)
No. (%) of shocks causing VT (>5 s duration)	8 (7.7)	4 (3.8)	12 (9.6)	10 (8.3)	19 (15.8)	7 (5.8)
No. of shocks causing asystole or PEA (>5 s duration) (% of shocks)	7 (6.7)	7 (6.7)	9 (7.3)	8 (6.5)	11 (9.2)	2 (1.6)
Cardiac output (l/min)	3.3 ± 0.3	3.3 ± 0.2	3.4 ± 0.2	3.8 ± 0.3	4.0 ± 0.3	3.8 ± 0.2

Data from part I experiments are based on equal-duration pulse waveforms. Data are presented as the mean value ± SE
LVEDP = left ventricular end-diastolic pressure; PEA = pulseless electrical activity; VT = ventricular tachycardia; other abbreviations as in Table 1.

of triphasic waveform superiority is not defined by this study.

Huang et al. (11) found that the efficacy of internal defibrillation by triphasic waveforms was sensitive to the phase duration. Several other studies have demonstrated that biphasic waveforms with the first phase longer than the second were more effective than those with the reverse sequence (16–19). This is consistent with our poor results for the biphasic equal-energy pulse shocks, where the duration of the first pulse was much shorter than that of the second pulse (3.3/11.1 ms).

Safety of biphasic and triphasic shocks. Data on chick embryo cells have suggested less post-shock dysfunction with triphasic shocks (8), but these data have not been confirmed in clinical studies. Our study demonstrates less triphasic shock-induced VT and asystole in pigs, which is consistent with the chick embryo studies. Less post-shock toxicity, if shown in humans, would be an important consideration in adopting a new defibrillation waveform.

Previous studies. Kidwai et al. (12) found no difference between biphasic and triphasic waveforms for transthoracic defibrillation. They studied rounded waveforms, not the truncated exponential waveforms we evaluated. They used a different measure of efficacy—the defibrillation threshold—rather than the energy versus success curves we used. These differences render a comparison of their study with ours difficult.

Study limitations. The duration of VF before the first shock was short (30 s). This simulates the usual clinical experience of an intensive care unit, but not that of a prehospital cardiac arrest. It is possible that the relative efficacy of triphasic versus biphasic shocks may vary with longer duration VF.

We used a custom-built defibrillator with a 115-μF capacitor to deliver biphasic and triphasic waveform shocks. Our results may not apply to triphasic waveforms delivered from other size capacitors.

The electrode pads we used are proportionately large for 18- to 28-kg pigs compared with 70-kg humans. Moreover, the shape of the porcine thorax and the position of the heart within the thorax are different in pigs compared with humans. These are further limitations of the porcine model. These species differences may explain the observation that the highest biphasic waveform success rate we observed was about 80%, whereas in humans, higher success rates have been observed (3).

We used a resistor in series to raise the impedance of the system to levels encountered clinically. The waveforms utilized in our custom-made defibrillator did not compensate for high impedance by automatically adjusting the duration and/or voltage of the pulses, as do some commercially available biphasic waveform defibrillators.

It is unlikely that the intrathoracic current distribution of the biphasic and triphasic shocks was altered by the series resistor we used, which was placed between the electrodes and defibrillator. However, in patients, differences in transthoracic impedance may be due to differences in body fat, soft and lung tissue, size, and distribution, which could substantially alter the intrathoracic and intracardiac current distribution. Our study provides no information on such possible differences in current flow within the chest.

There are innumerable variations of waveforms possible, and we could not hope to test them all. Instead, we chose to evaluate examples of two basic types of waveforms: equal-energy pulses and equal-duration pulses. This choice was arbitrary, and our results should not be taken to indicate that these are necessarily the optimal biphasic or triphasic waveforms.

In summary, triphasic waveforms appear to be a promising alternative for transthoracic defibrillation.

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