Fully Discharging Phases
A New Approach to Biphasic Waveforms for External Defibrillation

Yoshio Yamanouchi, MD; James E. Brewer, MS; Kenneth F. Olson, BS; Kent A. Mowrey, MS; Todor N. Mazgalev, PhD; Bruce L. Wilkoff, MD; Patrick J. Tchou, MD

Background—Phase-2 voltage and maximum pulse width are dependent on phase-1 pulse characteristics in a single-capacitor biphasic waveform. The use of 2 separate output capacitors avoids these limitations and may allow waveforms with lower defibrillation thresholds. A previous report also suggested that the optimal tilt may be >70%. This study was designed to determine an optimal biphasic waveform by use of a combination of 2 separate and fully (95% tilt) discharging capacitors.

Methods and Results—We performed 2 external defibrillation studies in a pig ventricular fibrillation model. In group 1, 9 waveforms from a combination of 3 phase-1 capacitor values (30, 60, and 120 μF) and 3 phase-2 capacitor values (0=monophasic, 1/3, and 1.0 times the phase-1 capacitor) were tested. Biphasic waveforms with phase-2 capacitors of 1/3 times that of phase 1 provided the highest defibrillation efficacy (stored energy and voltage) compared with corresponding monophasic and biphasic waveforms with the same capacitors in both phases except for waveforms with a 30-μF phase-1 capacitor. In group 2, 10 biphasic waveforms from a combination of 2 phase-1 capacitor values (30 and 60 μF) and 5 phase-2 capacitor values (10, 20, 30, 40, and 50 μF) were tested. In this range, phase-2 capacitor size was more critical for the 30-μF phase-1 than for the 60-μF phase-1 capacitor. The optimal combinations of fully discharging capacitors for defibrillation were 60/20 and 60/30 μF.

Conclusions—Phase-2 capacitor size plays an important role in reducing defibrillation energy in biphasic waveforms when 2 separate and fully discharging capacitors are used. (Circulation. 1999;100:826-831.)

Key Words: defibrillation ■ death, sudden ■ ventricles

The use of an exponential biphasic waveform has been shown to be superior to an exponential monophasic waveform in external1 as well as internal2,3 defibrillation. Use of a single capacitor for generating exponential biphasic waveforms poses several limitations, however. Increasing the phase-1 duration may not generate the optimal phase-2 leading-edge voltage or delivered charge, because phase-2 leading-edge voltage is dependent on phase-1 pulse width, phase-1 leading-edge voltage, capacitance, and impedance. Therefore, the optimal single-capacitor biphasic waveform may not generate the best combination of phase 1 and phase 2 compared with the optimal combination of 2 separate capacitors for the 2 phases.

In a previous report,4 we found that extending the phase-1 tilt of a biphasic waveform from 30% to 70% lowered the defibrillation threshold (DFT) energy when a 60-μF phase-1 capacitor was used. This finding suggested that the optical tilt may be >70%. Second, that previous report4 compared the use of a phase-2 capacitor (20 μF) that was smaller than the phase-1 capacitor with the use of same-size capacitors in both phases. The results indicated that the use of a smaller capacitor in phase 2, when charged to the same leading-edge voltage as phase 1, yielded the optimal DFT energies.

External defibrillation efficacy is influenced by multiple factors, such as electrode pad size,5,6 shock waveform,1,7–10 and sequential shocks.11 Because capacitor size may also play a role in determining external defibrillation efficacy,12 optimizing capacitor sizes may contribute to maximizing defibrillation efficacy. Theoretical models, assuming a 50-Ω impedance, have suggested that capacitors in the 30- to 60-μF range may provide the optimal capacitor for phase 1 of a biphasic waveform.13,14 Use of a smaller capacitor in a fully discharging capacitor waveform may be particularly important, because larger capacitors could result in exceedingly long pulse widths when the defibrillation shock is applied through a higher-impedance pathway. For example, for trans-thoracic impedance of 80 to 100 Ω,8–10,15 discharging a 120-μF capacitor to 95% tilt would take >30 ms.

The purpose of this study was to assess the optimal capacitor sizes (phase 1 and phase 2) for a fully discharging (95% tilt) biphasic waveform in the above-discussed range of 30, 60, and 120 μF that could be implemented in a standard external defibrillation device.

Received March 10, 1999; revision received April 28, 1999; accepted May 26, 1999.
From the Department of Cardiology, Cleveland Clinic Foundation, Cleveland, Ohio, and SurvivaLink Corp, Minneapolis, Minn (J.E.B., K.F.O.).
Correspondence to Patrick J. Tchou, MD, Director, Clinical Cardiac Electrophysiology, Department of Cardiology/F15, Cleveland Clinic Foundation, 9500 Euclid Ave, Cleveland, OH 44195. E-mail: tchoup@cesmtp.ccf.org
© 1999 American Heart Association, Inc.

Circulation is available at http://www.circulationaha.org
Methods

The use of experimental animals in this study was approved by the Animal Research Committee of the Cleveland Clinic Foundation and conformed to the recommendations of the American Heart Association on Research Animal Use.

Study Preparation and Surgical Procedure

Anesthetized pigs were used in this study. Animal preparation and surgical procedures have been described in detail in previous publications. Briefly, the swine were intubated with a cuffed endotracheal tube and ventilated with room air supplemented with oxygen through a Drager SAV respirator (North American Drager), which was adjusted as needed to maintain normal arterial blood gases. An external defibrillation lead (model 497, Intermedics Inc.) was inserted into the right ventricular (RV) apex through the right external jugular vein under fluoroscopy. Three adhesive pad electrodes, each with a surface area of 75 cm², were applied to the right upper pectoral, the left upper pectoral, and the cardiac apical area on shaved skin.

Defibrillation Protocol

The 3 adhesive pad electrodes and the RV apex defibrillation lead were connected to an external defibrillator custom-made by SurVivLink Corp. The function of this external defibrillator was described in detail in our previous publication. Ventricular fibrillation (VF) was induced by delivery of 60-Hz AC (15 V) for 3 seconds through the RV apex defibrillation lead and the left pectoral pad electrode. After VF sustained for 10 seconds, 1 of the test waveforms was delivered between the right upper pectoral pad electrode and the apical pad electrode at the end-expiration phase. The apical pad electrode was the anode for phase 1 of the biphasic waveforms. If defibrillation failed for the test shock waveform, a rescue shock (450 V) was delivered between the RV defibrillation lead and the left upper pectoral pad electrode. A recovery period of ≥3 minutes was allowed between each episode of VF. VF was not reinitiated until heart rate and blood pressure returned to the preshock values.

Defibrillation Waveforms

Two groups of experiments were performed for this report. In group 1, 3 phase-1 capacitor sizes (30, 60, and 120 µF) and 3 phase-2 capacitor sizes (0=monophasic, ½ of, and equal to phase-1 capacitor) were tested for a total of 9 different test shock waveforms. These 9 waveforms consisted of 3 exponential monophasic and 6 exponential biphasic waveforms, as illustrated in Figure 1A.

In group 2, a more detailed assessment of optimal phase-2 capacitor was performed using phase-1 capacitor sizes of 30 and 60 µF. Because of concerns regarding the potential length of phase-1 distal in a randomized order for all waveforms and the experimental limitation of the number of waveforms that can be tested in a single experiment, the 120-µF phase-1 capacitor was not evaluated. Five phase-2 capacitor sizes (10, 20, 30, 40, and 50 µF) were used in combination with the 30- and 60-µF phase-1 capacitor. Ten different exponential biphasic waveforms were tested in this group to evaluate defibrillation efficacy, as shown in Figure 1B.

Evaluation of Defibrillation Efficacy

Defibrillation efficacy of each waveform was estimated by V50, defined as the leading-edge voltage of the waveform associated with a 50% likelihood of successful defibrillation. V50 was measured by a previously described Bayesian estimation technique. Ten defibrillation tests were performed for each waveform to evaluate V50. The first shock phase-1 leading-edge voltage was 1650 V in all waveforms. Sequential step changes in voltage were 350, 200, 150, 100, 100, 50, 50, and 0 V. These steps in voltage change were either positive or negative, depending on failure or success in defibrillation of the preceding shock, respectively. E50 was the energy stored in the capacitors calculated from these V50 values.

In each animal, the effect of the first shock (1650 V) was tested first in a randomized order for all waveforms. Then, second shock voltages for the waveforms were determined, based on the result of the first, and were applied in random order as well. Thereafter, by the same procedure, the third through 10th shocks were delivered.

Statistical Analysis

Data in all DFT parameters were expressed as mean values±SD. Repeated-measures 1-way ANOVA was used to compare DFT parameters in group 1 and group 2. Pairwise comparisons of the waveforms were made for each parameter, with the least significant difference test used in group 1 and group 2. The null hypothesis was rejected for P<0.05.

Results

Group 1

A complete data set was obtained for 10 pigs (36±2 kg). All parameters at DFT are shown in Table 1.

Figure 2 shows the E50 of stored energy and V50 of phase-1 leading-edge voltage for all waveforms. For waveforms using a 30-µF phase-1 capacitor, there was a trend toward lower E50 in the biphasic waveforms, but this difference did not reach statistical significance. However, there was a significant drop in leading-edge voltage for the biphasic waveforms, with the lowest voltage seen in the 30/30-µF waveform. In the waveforms using a 60-µF phase-1 capacitor, the optimal E50 and V50 were seen with use of the 20-µF phase-2 capacitor (P=0.008 and P=0.013, respectively). In the waveforms using a 120-µF phase-1 capacitor, the optimal E50 and V50 were observed with a phase-2 capacitor of 40 µF. Interestingly, using a phase-2 capacitor equal to phase 1 (120/120 µF) resulted in E50 and V50 that were significantly higher even compared with the corresponding monophasic (120-µF) waveform. Thus, the biphasic waveform with a smaller phase-2 capacitor than phase-1 capacitor reduced the E50 of stored energy when 60- and 120-µF capacitors were used in phase 1. For a phase-1 30-µF capacitor, the 30/30-µF...
waveform appears to be optimal when considering $V_{50}$, even though the $E_{50}$ estimates did not reach statistical differences. These results suggest that a phase-2 capacitor of 20 to 40 $\mu$F may be optimal for a wide range of phase-1 capacitors.

**Group 2**

A complete data set was obtained for 10 pigs (33±4 kg). All parameters at DFT are shown in Table 2.

Figure 3 shows $E_{50}$ and $V_{50}$ of the experimental results. In both phase-1 capacitor waveforms, the $E_{50}$ and $V_{50}$ values showed a minimum at phase-2 capacitor values of 20 or 30 $\mu$F. For a 30-$\mu$F phase-1 capacitor, the $E_{50}$ and $V_{50}$ rose markedly once phase-2 capacitor size exceeded 30 $\mu$F. For a 60-$\mu$F phase-1 capacitor, however, this rise was much less prominent. This difference may be related to the ratio of phase-1 to phase-2 capacitors and their effects on pulse width of the phases.

**Discussion**

The results of this study show that DFT voltage and/or energy can be significantly lowered with the use of biphasic fully discharging capacitor waveforms compared with their corresponding monophasic waveforms. It is interesting to compare the effects of the phase-2 capacitor on the DFT. When a 30-$\mu$F phase-1 capacitor was used, the addition of a phase-2 capacitor (10 or 30 $\mu$F) lowered both DFT energy and voltage by ≈40%. The lowest DFT was associated with the 30-$\mu$F phase-2 capacitor. With the 60- and 120-$\mu$F phase-1 capacitors, adding the corresponding 20- and 40-$\mu$F phase-2 capacitors had similar effects in lowering the DFT. However, when the corresponding phase-2 capacitors were made equal to the phase-1 capacitors, DFTs increased again, and for the 120-$\mu$F capacitors, biphasic thresholds were even higher than monophasic thresholds. These results would suggest that the optimal phase-2 capacitor for 30- to 120-$\mu$F phase-1 capacitors is in the range of 20 to 40 $\mu$F regardless of the capacitor used in phase 1. The results of these experiments showed that the capacitor combinations of 60/20 and 120/40 $\mu$F were clearly superior to the corresponding ones using the same capacitors for both phase 1 and phase 2 (60/60 and 120/120 $\mu$F). Perhaps because 30 $\mu$F was in the range of the optimal phase-2 capacitor, the difference between the 30/10- and the 30/30-$\mu$F waveforms was small.

The results shown in Table 1 reveal that the mean impedances in our experimental model were in the 40- to 50-$\Omega$ range. However, typical transthoracic impedances for human defibrillation are higher, 60 to 80 $\Omega$, with values in the 80- to 100-$\Omega$ range seen occasionally.\(^8\) –\(^{10}\) The use of a 120-$\mu$F capacitor may be problematic in this impedance range. Based on the pulse widths shown in Table 1, one can extrapolate that the use of the same 120-$\mu$F waveforms in humans can extend the pulse widths to the 20- to 30-ms range. Such long pulse widths are likely to be not as effective for defibrillation, because their duration will be well beyond the chronaxie of the defibrillation strength-duration curves.\(^{14}\) Thus, group 2 data shown in Table 2 were limited to a more detailed analysis of the 30- and 60-$\mu$F waveforms.

As illustrated in Figure 3, the pattern of changes in the DFT voltage and energy associated with changing phase-2 capaci-

---

**TABLE 1. DFT Parameters and Waveform Characteristics in Group 1**

<table>
<thead>
<tr>
<th>Waveform</th>
<th>Capacitor Size in Phase 1/2, $\mu$F</th>
<th>Stored Energy, J</th>
<th>Phase-1 Leading-Edge Voltage, V</th>
<th>Phase-1 Pulse Impedance, $\Omega$</th>
<th>Phase-1 Pulse Width, ms</th>
<th>Phase-2 Pulse Width, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/0</td>
<td>101±16†</td>
<td>2586±212</td>
<td>40±3</td>
<td>3.5±0.2</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>30/10</td>
<td>62±24†</td>
<td>1724±363</td>
<td>41±3</td>
<td>3.6±0.3</td>
<td>1.2±0.1</td>
<td></td>
</tr>
<tr>
<td>30/30</td>
<td>57±20†</td>
<td>1365±234</td>
<td>42±3</td>
<td>3.6±0.2</td>
<td>3.5±0.2</td>
<td></td>
</tr>
<tr>
<td>60/0</td>
<td>129±40‡</td>
<td>2050±327</td>
<td>40±4</td>
<td>7.0±0.5</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>60/20</td>
<td>43±15§</td>
<td>1022±191</td>
<td>44±5</td>
<td>7.4±0.6</td>
<td>2.4±0.2</td>
<td></td>
</tr>
<tr>
<td>60/60</td>
<td>123±62†</td>
<td>1386±369</td>
<td>42±5</td>
<td>7.2±0.6</td>
<td>6.9±0.6</td>
<td></td>
</tr>
<tr>
<td>120/30</td>
<td>229±103§</td>
<td>1909±429</td>
<td>40±3</td>
<td>14.0±1.0</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>120/40</td>
<td>44±21*</td>
<td>726±176</td>
<td>45±5</td>
<td>14.7±1.2</td>
<td>4.8±0.4</td>
<td></td>
</tr>
<tr>
<td>120/120</td>
<td>650±206</td>
<td>2299±388</td>
<td>40±4</td>
<td>13.9±1.1</td>
<td>13.3±1.0</td>
<td></td>
</tr>
</tbody>
</table>

*P<0.05 vs 60/0, 60/60, 120/0, and 120/120.
†P<0.05 vs 60/0, 120/0, and 120/120.
‡P<0.05 vs 120/0 and 120/120.
§P<0.05 vs 120/120.

All pairwise comparisons of phase-1 leading-edge voltages are significant ($P<0.05$) except among comparison of same-size phase-1 capacitor waveforms. All pairwise comparisons of phase-2 pulse width are significant ($P<0.05$).
A recent external defibrillation study\(^1\) showed the superiority of single-capacitor biphasic waveforms over exponential monophasic waveforms. However, there are a few limitations in such a single-capacitor biphasic waveform. Maximizing...
the phase-1 pulse width may not generate the optimal phase-2 leading-edge voltage or charge transfer, because phase-2 leading-edge voltage is dependent on phase-1 pulse width. In addition, several recent defibrillation studies have shown that a biphasic waveform with a smaller phase-2 capacitor can achieve lower DFT energy when a phase-1 capacitor of 60 μF is used. Therefore, optimal biphasic waveforms may be best generated with 2 separate capacitors, 1 for phase 1 and 1 for phase 2.

As shown in Figure 2, the addition of an appropriate phase-2 capacitor can improve the E50 of the biphasic waveform that obtained with the corresponding monophasic waveform. However, the relative improvement of the E50 appears to be greater when larger capacitors are used in phase 1. Specifically, the biphasic waveforms of 30/10, 60/20, and 120/40 μF reduced E50 by 38%, 67%, and 81%, respectively, compared with their respective monophasic waveforms. Thus, the beneficial effects of adding a phase-2 capacitor to the monophasic waveform appear to depend on the capacitor size in phase 1. Although the monophasic 120-μF waveform had the highest E50 of the 3 capacitors, the greater improvement in E50 seen with the addition of phase 2 made the 120/40-μF waveform perform as well as the 60/20-, 30/10-, and 30/30-μF waveforms. Another interesting observation is the effect of having the same capacitor/pulse width in both phases of the biphasic waveform. Although the 120/120-μF waveform had a poor E50 compared with the 120/40-μF waveform, the difference was much less prominent when the 60/60-μF and the 60/20-μF waveforms were compared, and the difference was nonexistent when the 30/30-μF and the 30/10-μF waveforms were compared. This observation would suggest that the optimal capacitor for a phase-2 fully discharging waveform may be fairly constant, ≈20 to 40 μF, regardless of the phase-1 capacitor used. Because phase-2 capacitors were charged to the same voltage as phase-1 capacitors in these experiments, this observation would imply that the actual need for charge transfer in phase 2 may be less for higher-capacitor phase-1 waveforms where the leading-edge voltage is lower, even though the pulse width is longer, at least within the impedance range seen in our experimental preparation. Thus, the need for phase-2 charge transfer may be related to the leading-edge voltage of phase 1 regardless of the phase-1 capacitor.

Application of the 120-μF Capacitor to Human External Defibrillation
The impedance for external shock in the human chest is 60 to 80 Ω and may exceed 100 Ω in some cases. Conversely, the shock impedance of our pig model was ≈40 to 50 Ω in this study. Although the 120/40-μF biphasic waveform performed quite well, as evidenced by the data presented in Table 1 and Figure 2, its applicability to higher-impedance pathways may be problematic. The phase-1 pulse width of the 120-μF waveforms tested here was ≈14 ms with 40-Ω impedance. For clinical circumstances, this phase-1 pulse width may become 20 to 30 ms because of the higher impedance and may be even higher in high-impedance cases. Such a long pulse width would most likely be inefficient for external defibrillation. Thus, our group 2 experiments did not include this capacitor.

Clinical Implications
To facilitate widespread dissemination and public use of such external defibrillators, it is important that these devices be reliable and appropriately priced. Thus, technological approaches that would minimize the cost of construction may be an important consideration in public access defibrillators.

Full-tilt waveforms have several potential advantages over traditional biphasic waveform designs. These advantages include higher reliability and simpler design. All of this translates into a potentially better defibrillator. In a single-capacitor biphasic waveform, a switching system is necessary to change polarity at a high voltage of phase reversal and for truncation of phase 2. Conventional biphasic waveforms have always been generated with an H-bridge-style construction. This method used electronic switches to reverse the capacitor during the middle of the discharge cycle. Such a reversal requires switches that are capable of controlling both high currents and high voltages. Switching these high currents necessitates the use of isolated-gate, bipolar transistors (IGBTs), which are fairly bulky and relatively expensive. Because the polarity of the capacitor must be totally reversed, IGBTs are required. All 4 must be carefully sequenced to properly reverse the voltage. In addition, dump resistors that are frequently used to dispose of residual charges on a capacitor after truncation would not be necessary with a nearly full-tilt waveform.

A 2-capacitor construction to implement the waveforms reported here would simplify the switching requirements, because the polarity of the capacitors does not need to be reversed. Two separate capacitor banks would be used for the 2 phases. This waveform design uses the same leading-edge voltage in both phases, which allows the use of a single-charge transformer. Because virtually all of the energy is delivered to the patient, truncation circuitry is greatly simplified. This simplification means fewer parts and less energy switching, which improves the reliability of the system while reducing space and power requirements.

Conclusions
The major findings of this external defibrillation study are as follows. (1) For biphasic waveforms using 2 separate and almost completely discharging (95% tilt) capacitors, the phase-2 capacitor size is an important factor in maximizing defibrillation efficacy. (2) Biphasic waveforms using 2 separate and fully discharging capacitors appear to function best with a phase-2 capacitor ≈20 to 40 μF for phase-1 capacitors in the 30- to 120-μF range. (3) In an external defibrillator for human use, the 60/20- or 60/30-μF model may be the optimal choice among the waveforms tested here, because the 120-μF capacitor may generate exceedingly long pulse widths and the 30-μF model would use higher voltages, possibly generating greater costs without additional benefits. (4) The use of simpler components in a high-tilt biphasic waveform as described here may improve the reliability and the expense of manufacturing external defibrillators.
Acknowledgments

This work was supported by a grant from the SurVivaLink Corporation. We would like to thank Donald G. Hills for his technical assistance in the care of the animals before and during the experiments.

References

Fully Discharging Phases: A New Approach to Biphasic Waveforms for External Defibrillation

Yoshio Yamanouchi, James E. Brewer, Kenneth F. Olson, Kent A. Mowrey, Todor N. Mazgalev, Bruce L. Wilkoff and Patrick J. Tchou

_Circulation_. 1999;100:826-831
doi: 10.1161/01.CIR.100.8.826

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1999 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/100/8/826

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in _Circulation_ can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to _Circulation_ is online at:
http://circ.ahajournals.org/subscriptions/