Ventricular Defibrillation With Triphasic Waveforms

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Background—It has been reported that triphasic defibrillation waveforms cause less myocardial injury than biphasic waveforms. This study compared the defibrillation thresholds (DFTs) of triphasic and biphasic waveforms.

Methods and Results—DFTs were determined for a transvenous lead system and a 300-μF-capacitor defibrillator. In 8 pigs (group 1), DFTs were determined for 5 triphasic waveforms with tilts of 80%, 83%, and 86% and for 1 biphasic waveform. DFTs were determined in another 8 pigs (group 2) for 2 triphasic and 4 biphasic waveforms with tilts of 43%, 49%, and 56%. In both groups, a biphasic waveform from a 140-μF-capacitor defibrillator was also evaluated, and both shock polarities were tested for each waveform. In group 1, with the 300-μF-capacitor defibrillator, the leading-edge voltage and energy stored at DFT were significantly lower for triphasic waveforms with phase-duration ratios of 50/33/17 and an anode at the right ventricular electrode for phase 1 than for biphasic waveforms (P<0.001). In group 2, the stored energy of triphasic waveforms with 56% and 49% tilt was significantly lower than that of biphasic waveforms with the same tilts for anodal but not cathodal phase 1 at the right ventricular electrode. Electrode polarity significantly affected the DFT of triphasic waveforms for both studies.

Conclusions—Some 80% tilt triphasic waveforms defibrillate more efficiently than biphasic waveforms with a 300-μF-capacitor defibrillator. The triphasic waveforms for both groups were not superior to 140-μF-capacitor biphasic waveforms. The efficacy of triphasic waveforms depends on phase durations and electrode polarity. (Circulation. 2000;101:1324-1328.)

Key Words: defibrillation ■ waveforms ■ ventricles

Biphasic waveforms may defibrillate better than monophasic waveforms because they have a lower defibrillation threshold (DFT)1,2 and cause less myocardial damage.3–7 However, the optimal second-phase strength for minimization of the DFT is much larger than that for minimization of myocardial damage. Jones8 suggested that the benefits of both effects could be harnessed through the use of a triphasic waveform, in which the second phase is the larger strength, to lower the DFT, and the third phase is the lower strength, to minimize damage. They postulated that the first phase acts as a “conditioning prepulse,” the second phase as a “defibrillating” phase, and the third phase as a “healing postpulse.” However, subsequent studies in animals and humans9–13 failed to demonstrate the superiority of triphasic waveforms.

These disappointing results may have been caused by suboptimal electrode polarity and phase durations. An anode at the right ventricular (RV) electrode resulted in a lower DFT than a cathode for some monophasic waveforms.14–17 Biphasic waveforms in which the second phase was ≥2 ms longer than the first phase also had a lower DFT when the RV electrode was an anode. In contrast, alterations in polarity of biphasic shocks in which the second phase was equal to or shorter than that of the first phase had no effect on the DFTs.17–23 Addition of a 1-ms second phase to monophasic waveforms of 3 to 8 ms duration abolished the effect of electrode polarity on the DFT, even though the second phase accounted for as little as 2.4% of the total delivered energy.17

These results suggest that the polarity of both phases can be important for defibrillation and that for both phases, an anode at the RV electrode can be better than a cathode. It is, of course, impossible to set both phases of a biphasic waveform to the same polarity and maintain the low DFT caused by polarity reversal between the 2 phases. However, this can be achieved with a triphasic waveform. We tested the hypotheses that a triphasic waveform with the first and third phases with the RV electrode as anode defibrillated more efficiently than some biphasic waveforms and more efficiently than triphasic waveforms with the reversed polarity. We also tested the hypothesis that defibrillation with a triphasic waveform of optimal phase ratio and polarity would be more efficient than a biphasic waveform.
Results

Protocol 1

In all of the results below, anodal or cathodal refers to the polarity of the RV electrode during the first phase of the waveform. Both the waveform and electrode polarity had a significant effect (P<0.001 for leading-edge voltage and stored energy, respectively) on the DFT (Figures 1 and 2). The leading-edge voltage of the anodal triphasic waveform with the phase-duration distribution 50/33/17 (Figure 1F) was significantly lower than that of anodal biphasic waveforms with the phase-duration ratio of 60/40 with either the 300- or 140-μF capacitors (Figures 1A and 1G). Although the point estimates of the means of the leading-edge voltage and energy DFTs for the anodal triphasic waveforms with phase-duration distributions of 60/30/10, 60/20/20, and 55/36/9 were lower than for the biphasic waveforms with a phase-duration ratio of 60/40, this difference did not reach statistical significance. Similarly, there was no significant difference in the total stored energy between the anodal triphasic 300-μF waveform with a phase-duration distribution of 50/33/17 and the 60/40 biphasic waveform with the 140-μF capacitor.

For 300-μF cathodal waveforms, the leading-edge voltage and total energy DFTs were significantly higher for the 60/10/30 triphasic waveform than for the 60/40 biphasic waveform with a 300-μF capacitor of the same polarity; †leading-edge voltages that significantly differed from 60/40 biphasic waveform with a 140-μF capacitor.

Mean Leading Edge Voltage at DFT (Protocol 1)

![Mean Leading Edge Voltage at DFT (Protocol 1)](image1)

Mean Stored Energy at DFT (Protocol 1)

![Mean Stored Energy at DFT (Protocol 1)](image2)
waveform. The more conservative Student-Neuman-Keuls test indicated that the stored energy requirement of the 60/10/30 cathodal triphasic waveform was significantly higher than the other waveforms (Figure 2). The 60/10/30 cathodal triphasic waveform also had significantly higher leading-edge voltage requirements than all other waveforms except the 55/36/9 cathodal triphasic waveform and 60/40 cathodal biphasic waveform with the 140-μF capacitor.

The leading-edge voltage and stored energy of the DFTs of the triphasic waveforms of duration ratios 60/10/30 and 50/33/17 were significantly lower when the RV electrode was an anode than a cathode. There was no statistically significant difference in leading-edge voltage or total energy DFT for the 2 shock polarities for the other waveforms.

Protocol 2
Both waveform and electrode polarity had a significant effect on the stored energy of the DFT (Figures 3 and 4). Factorial ANOVA analysis indicated that the stored energy requirements of the anodal triphasic waveforms with 56% and 49% tilts (Figures 4A and 4D) were significantly lower than those of anodal biphasic waveforms with the same tilts (Figures 4C and 4F).

Leading-edge voltage DFTs were significantly lower for the anodal triphasic waveforms with 56% tilt and 49% tilt (Figures 3A and 3D) than for the biphasic waveforms with the same tilts (Figures 3C and 3F) by Student’s t test (P<0.05). However, the differences were not statistically significant when the general factorial ANOVA test was used, in which

![Mean Leading Edge Voltage at DFT (Protocol 2)](image)

![Mean Stored Energy at DFT (Protocol 2)](image)

**Figure 3.** Waveforms for protocol 2 and mean and SDs of leading-edge voltages for each waveform. A through F, 300-μF-capacitor waveforms; G, 140-μF-capacitor waveform. Numbers give relative shock duration (of total duration, in percent). Dashed lines have a similar indication as for Figure 1 and indicate points on waveforms with same duration. *Paired points that differed significantly from each other (P<0.05).

**Figure 4.** Mean and SDs of stored energy DFT for each waveform from protocol 2. *Paired points that differed significantly (P<0.05). †Stored energy for triphasic waveforms that significantly differed from 50/50 biphasic waveform with a 300-μF capacitor. See legend to Figure 3 for additional information.
the triphasic waveform was used as the reference category for comparison with the biphasic waveforms. Both triphasic waveforms with anodal first phase defibrillated with a lower leading-edge voltage and energy than the cathodal first phase \( (P < 0.05) \).

The leading-edge voltage DFTs for most 300-\( \mu \)F waveforms were significantly lower than those of the biphasic 140-\( \mu \)F waveforms. However, there were no significant differences among the stored energies between the 300- and 140-\( \mu \)F waveforms.

There was no significant difference in impedance for any waveform or for any waveform phase by ANOVA. The mean impedance was 45±6 \( \Omega \).

**Discussion**

Our principal finding is that some but not all 300-\( \mu \)F triphasic waveforms have a lower DFT than some comparable biphasic waveforms, with the efficacy of the triphasic waveform depending on the phase durations. This study also indicates that electrode polarity has an important effect on the DFT of triphasic waveforms; when the initial and final phases at the RV electrode were anodal, the DFT appeared lower than when they were cathodal, with this difference reaching statistical significance in some comparisons. Lowest mean DFTs were observed, however, for cathodal biphasic waveforms, with both 140- and 300-\( \mu \)F capacitors in protocol 2, although the differences compared with the lowest anodal triphasic waveform DFT did not reach statistical significance.

**Reasons for the Efficacy of Triphasic Waveform Defibrillation**

One mechanism underlying the lower DFT of biphasic than monophasic waveforms may be the improved ability of biphasic waveforms to excite myocardial cells to their relative refractory period during fibrillation for successful termination of fibrillation.\(^24\)\(^\text{25}\) The amplitude of the second phase of these biphasic waveforms should range from 50\% to 200\% of the first phase.\(^26\) A biphasic waveform with a second-phase amplitude that was 5\% to 20\% of the first phase reduced shock-induced dysfunction\(^2\) and decreased the incidence of atrioventricular block.\(^4\) Thus, the optimum strength of the second phase that minimizes DFT is much larger than the optimum strength that minimizes damage.

To try to gain the benefits of both effects, Jones\(^8\) suggested a triphasic defibrillation waveform, in which the second phase was of the optimum strength for lowering the DFT and the third phase was smaller and optimized to minimize myocardial damage by the shock. They demonstrated in chick embryo cells that triphasic waveforms had a greater safety factor than biphasic waveforms.\(^8\) The safety factor was defined as the ratio of the minimum shock voltage gradient producing a 4-second arrest to the minimum shock voltage gradient capturing the tissue.

The present study is consistent with Jones’ prediction in that the triphasic waveform with the lower DFT had a third-phase amplitude that was 18\% of the first-phase amplitude (Figures 1F and 2F). However, another triphasic waveform with an 18\% third-phase amplitude did not significantly reduce the DFT compared with a biphasic waveform (Figures 1A, 1E, 2A, and 2E). Further studies are needed to confirm whether these triphasic waveforms reduce shock-associated dysfunction.

Previous studies have suggested that the lower DFT with polarity reversal depends on either the total biphasic shock duration\(^18\) or second-phase duration.\(^17\) The present study also shows that the effect of shock polarity on the DFT depends on total or individual phase durations of triphasic waveforms. The triphasic waveforms with a lower DFT in the present study may combine the optimal total or individual phase durations and optimal electrode polarity. Additional studies are needed to further define how phase duration affects the DFT of triphasic waveforms with polarity reversal.

**Comparison With Previous Triphasic Studies**

The few previous studies reported that triphasic waveforms defibrillate with a lower DFT than monophasic waveforms but with an equal or higher DFT than biphasic waveforms.\(^9\)\(^\text{13}\) This study demonstrates that 300-\( \mu \)F triphasic waveforms, with a phase-duration ratio of 50/33/17 and a tilt of 86\%, offer a slight advantage over biphasic waveforms in defibrillation efficacy. Consistent with previous reports, the other triphasic waveforms tested in the present study were no more effective than the biphasic waveforms and in some cases were less effective.

The durations of the 2 phases of a biphasic waveform markedly affect defibrillation efficacy.\(^2\)\(^27\)\(^28\) For monophasic shocks, when the RV electrode is an anode, the DFT is significantly lower than when it is a cathode.\(^23\) In some cases, polarity appears to affect the efficacy of biphasic waveforms, whereas in other cases it does not.\(^17\)\(^20\)

This study demonstrates that the efficacy of defibrillation for triphasic waveforms is sensitive to both phase duration and electrode polarity. An anodal initial phase at the RV electrode for the triphasic waveform had a lower DFT than a cathodal initial phase. Chapman et al\(^10\) used the cathodal RV electrode configuration for their study and did not show any benefit for defibrillation with a triphasic waveform. For the triphasic waveforms used by Stellbrink et al\(^14\) and Chapman et al\(^16\) phase 1 and phase 3 were each 25\% and phase 2 was 50\% of the total duration. These are not optimal phase-duration ratios according to the findings from the present study and our previous biphasic waveform study.\(^17\)

**Study Limitations**

This study only tested 300-\( \mu \)F-capacitor triphasic waveforms; it is unknown whether the findings would also apply to triphasic waveforms delivered from other-size capacitors. We chose the 300-\( \mu \)F capacitor because it has been shown that large-capacitor waveforms reduce DFT peak voltage without increasing DFT energy.\(^29\)\(^30\) Reducing peak voltage may decrease detrimental shock effects and may allow lower voltage ratings of the electronic components in the defibrillator, which would allow the size of the components to be reduced.

**Clinical Significance**

The best triphasic waveform had a slightly lower DFT than some comparable biphasic waveforms. This benefit is prob-
ably not sufficiently great to merit alteration of the hardware construction of the defibrillator. However, most defibrillators that can deliver a biphasic waveform already contain the switches and other hardware necessary for delivery of a triphasic waveform. Therefore, slight alteration of the software in the defibrillator to switch the waveform a second time to deliver the third phase is the main change required for delivery of a triphasic shock. Thus, if a triphasic waveform is shown to have similar benefit in patients, its clinical use may be justified.

It has also been suggested that triphasic waveforms have less-detrimental effects than either monophasic or biphasic waveforms. However, this suggestion is based on findings in a culture of chick embryo cells. This possibility needs to be confirmed in intact hearts.

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References

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