Comparative Efficacy of Triphasic and Biphasic Internal Defibrillation

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Summary

Biphasic defibrillation shocks have proven to be superior to monophasic shocks and require lower energy for successful defibrillation. Triphasic shocks may lead to fewer post-shock arrhythmias, but results about their efficacy compared to biphasic shocks are inconclusive. This may be due to non-optimized impulse duration for the respective waveforms. The shock strength-impulse duration relationship of biphasic and triphasic internal defibrillation shocks delivered by a 150 mF capacitor was evaluated in eight pigs. The defibrillation threshold (DFT) was determined by a step-down/step-up protocol. The defibrillation efficacy was then compared at the respective optimal impulse duration. For triphasic shocks the DFT was lowest at a total shock duration of 8 ms, whereas it was lowest for biphasic shocks at a total shock duration of 10 ms. Strength-duration curves for both biphasic and triphasic shocks resembled inversely bell-shaped curves. At optimal shock duration, DFTs were significantly lower for biphasic than for triphasic shocks. In summary, biphasic and triphasic shocks have DFT minima at different total shock durations. Comparing biphasic and triphasic waveforms at their optimal waveform durations, significantly higher DFTs were observed for triphasic waveforms.

Key Words

Defibrillation threshold, biphasic, triphasic, sudden cardiac death

Introduction

Since the introduction of implantable cardioverter/defibrillators (ICDs), total mortality after survived sudden cardiac arrest has been dramatically reduced [1,2]. In addition to showing the benefit for secondary prevention of sudden cardiac death, several trials have highlighted the potential of ICDs for primary prevention of sudden cardiac death in patients with severely reduced left ventricular function [3-5]. With this in mind, the number of ICD implantations may dramatically increase in the future, imposing a substantial financial burden on health care systems. Therefore, the introduction of less expensive ICDs with a limited maximum shock energy and lower battery capacity to deliver a limited number of defibrillation shocks has been advocated [6,7]. Therefore, it may be desirable to reduce the defibrillation energy requirement to the lowest level possible [8].

There are different ways to reduce the energy required for successful defibrillation, such as adjusting the shock duration, shock polarity, or lead configuration [9-11]. Significantly, the waveform itself has been shown to have a major impact on defibrillation energy requirements: current ICDs deliver truncated exponential waveforms that are discharged by a capacitor. Technically, such shocks can be delivered in single or multiple phases. For example, biphasic shock waveforms with two shock phases of opposite polarities have consistently been proven to yield lower defibrillation thresholds (DFTs) than monophasic waveforms [12-19]. There is some experimental evidence from studies in cell cultures that triphasic shock waveforms may improve defibrillation efficacy by reducing myocardial injury [20]. However, so far this could not be proven in clinical studies [21]. By contrast, an experimental study by Huang [22] reported that altering the ratio of the length of the shock phases of triphasic shocks may yield lower DFTs for triphasic as compared to biphasic shocks in some instances.

The energy requirements for successful defibrillation critically depend on the pulse duration [9,11,23,24]. While it is well-known that the shock strength-duration curves of monophasic and biphasic shocks resemble inversely bell-shaped curves [9,25,26], no such evidence is present for triphasic defibrillation shocks. An incorrect estimation of the defibrillation efficacy can be avoided by comparing different waveforms at their optimal waveform durations with minimal voltage at the DFT. Consequently, diverging results on the comparative defibrillation efficacy of biphasic versus triphasic shocks may be due in part to non-optimized total shock durations of the respective waveforms.

In this study, we investigated the shape of the shock strength-duration curve of internal triphasic defibrillation shocks in an animal model. To evaluate the true defibrillation potential of triphasic shocks, we then intraindividually compared the defibrillation efficacy of triphasic and biphasic shocks each at optimal total shock duration.

Materials and Methods

In total, eight pigs (70.0 ± 8.5 kg) were anesthetized with azaperone (2 mg/kg i.m.), atropine (0.14 mg/kg i.m.), and ketamine (20 mg/kg i.m.). Anesthesia was maintained by ventilation with N_2O and O_2 (ratio 3:1, Servo respirator, Siemens, Germany) and sodium pentobarbital infusion. An arterial line was placed in the carotid artery to monitor blood pressure. Arterial and central venous blood samples were taken every 30 min in order to analyze electrolytes and blood gases; abnormal values were instantly corrected. A defibrillation lead (Ventritex-SP-01, Ventritex, USA) was inserted through the left external jugular vein and then positioned in the right ventricular apex (RVA). Thereby, the distal shock coil of the lead was positioned in the right ventricular apex and the proximal coil in the superior vena cava. An ICD shell (Ventritex Contour, Ventritex) was placed in the left pectoral muscle to serve as a defibrillation electrode ("active can").

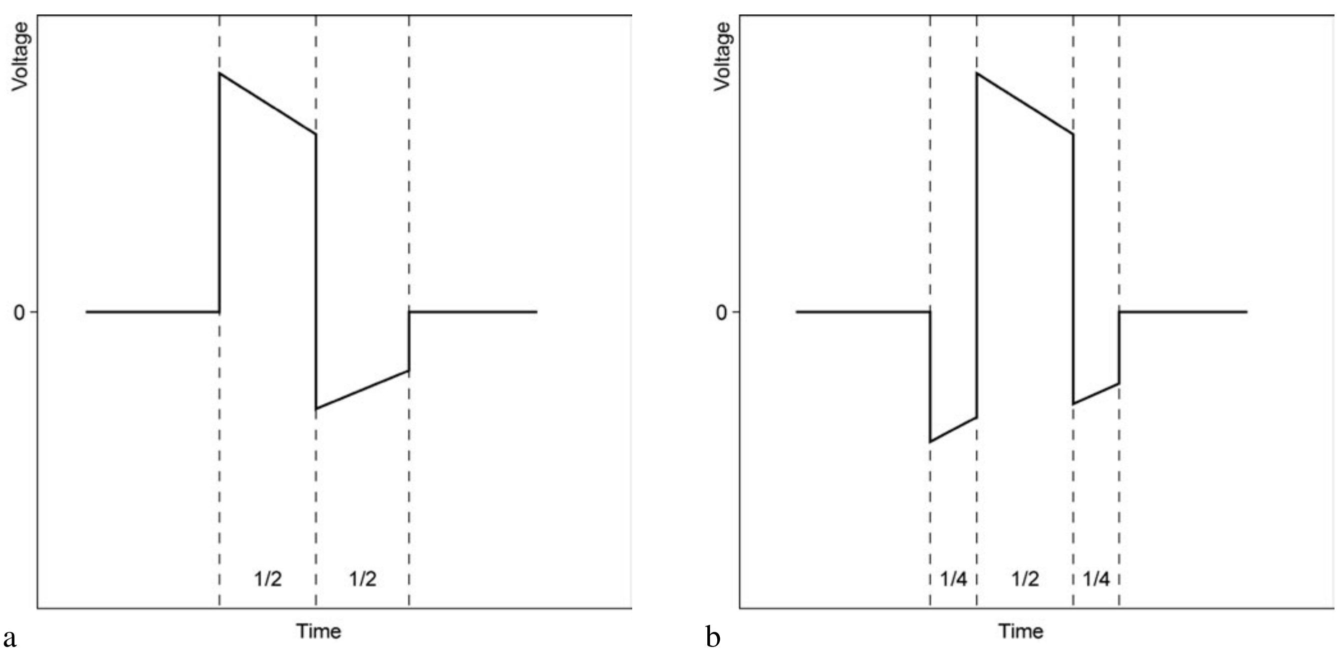

Figure 1. Panel a) Biphasic waveform. The duration of phase 1 and phase 2 was equal. The leading edge voltage of phase 2 was half the trailing edge voltage of phase 1. Panel b) Triphasic waveform. Phase 1, 2, and 3 durations made up for ¼, ½, and ¼, respectively, of the total shock duration. The leading edge voltage of phase 1 was half the programmed voltage; the leading edge of phase 2 was half the programmed voltage plus the trailing edge voltage of phase 1. The leading edge voltage of the third phase was the trailing edge of the first phase minus half of the difference between the leading and trailing edge voltages of the second phase.

Shocks were delivered by a 150 µF capacitor for all shock phases (Ventritex HVS-02, Ventritex). The RVA coil served as the anode during phase 1 of biphasic or triphasic shocks. The defibrillation coil in the superior vena cava and the subpectoral ICD shell were used as a common cathode during phase 1. For biphasic shocks, the duration of phase 1 and phase 2 was equally long. The leading edge voltage of phase 2 was set at half the trailing edge voltage of phase 1. The biphasic waveform is schematically depicted in Figure 1. For triphasic shocks, the ratio of the length of the 3 shock phases was 1:2:1 (phase 1: phase 2: phase 3) based on the settings of the same capacitor type. The leading edge of phase 1 was half the programmed voltage, whereas the leading edge voltage of phase 2 was half the programmed voltage plus the trailing edge voltage of phase 1. The leading edge voltage of phase 3 was adjusted to equal the trailing edge voltage of phase 1 minus half of the difference between the leading and trailing edge voltage of phase 2 (Figure 1).

Biphasic and triphasic shocks were delivered in randomized order using eight different total shock durations (2, 4, 6, 8, 10, 12, 14, 16 ms). For both waveforms, the impedance of the tissue/electrode system was calculated by dividing peak shock voltage by peak current.

Ventricular fibrillation (VF) was induced via the right ventricular pacing leads with a burst of 50 Hz of alternating current lasting 1.5 s at twice the diastolic pacing threshold. Defibrillation shocks were delivered 10 s after the onset of VF. Starting with a peak shock voltage of 710 V, the DFTs were determined using a step-down/step-up protocol with a step-down size of 80 V, a step-up size of 40 V, and final steps of 20 V. The shock voltage was reduced by 80 V until the first defibrillation failure occurred. If a shock failed to terminate VF, an internal 990 V shock was applied.

The shock voltage for the next shock was then increased by 40 V. Successful defibrillation at this energy level led to a decrease, unsuccessful defibrillation to an increase of 20 V. The lowest voltage at which successful defibrillation occurred was defined as DFT. After each VF episode, we waited at least 3 min until VF was reinduced to allow for normalization of blood pressure and heart rate. To ensure a stable DFT, a biphasic DFT at a total shock duration of 10 ms was determined at the beginning of the experiment and hourly thereafter. If the DFT differed by more than 40 V for this control waveform, the pig was excluded from analysis.

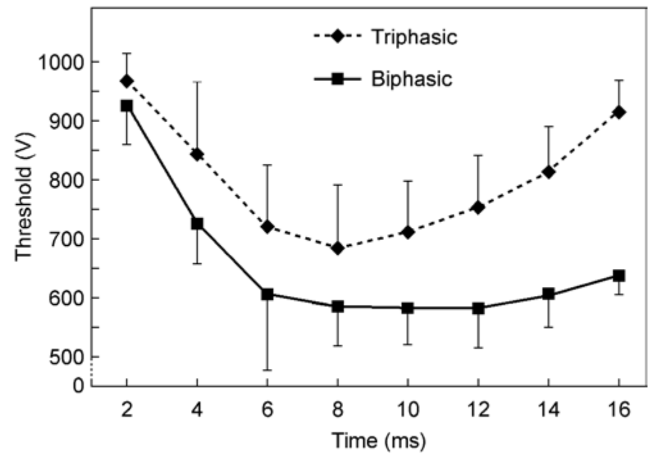

Figure 2. Defibrillation thresholds of biphasic and triphasic waveforms. The curves for both biphasic and triphasic waveforms resemble inversely bell-shaped curves. DFTs at optimal total shock duration (10 ms for biphasic and 8 ms for triphasic waveforms) were significantly lower for biphasic waveforms.

Results

No animal was excluded from analysis due to an unstable DFT. For biphasic waveforms, the DFT significantly depended on the total shock duration ($p = 0.003$, ANOVA). The shock strength-duration curve for biphasic shocks resembled an inverse bell-shaped curve. The lowest DFTs were obtained at a total shock duration of 10 ms ($p < 0.05$ vs. shock durations of 2, 4, 12, 14, 16, 18 ms; Figure 2).

For triphasic waveforms, the total shock duration also significantly affected the DFT ($p < 0.005$, ANOVA). Similar to biphasic waveforms, the shock strength-duration curve for triphasic shocks had an inverse hyperbolic shape. For triphasic shock forms, the lowest DFT values were obtained at a total shock duration of 8 ms ($p < 0.05$ vs. shock durations of 2 ms, 4 ms; Figure 2).

The peak voltage of biphasic shocks at the shock duration with the lowest DFT (10 ms) was significantly lower than the peak voltage of triphasic shocks at the shock duration that yielded the lowest DFT for triphasic shocks (8 ms; 685.0 ± 108.2 V for biphasic and 583.8 ± 62.8 V for triphasic waveforms, $p < 0.05$). The impedance of biphasic and triphasic waveforms did not differ significantly (biphasic shocks: 30.6 ± 3.1 Ω vs. triphasic shocks: 30.6 ± 3.0 Ω, p = not significant).

Discussion

Previous studies using cultured myocardial chick cells have demonstrated fewer post-shock arrhythmias for specifically shaped triphasic shocks than for monophasic or biphasic shocks [20]. This led to the hypothesis that triphasic shocks might increase the safety factor for cardiac defibrillation. However, shocks were not delivered during VF in that study, and post-shock contractile arrest was used to quantify post-shock arrhythmia. For the specific triphasic waveform tested in that study, the peak voltages of phase 1 and phase 2 were equal, whereas the voltage amplitude of the third phase consisted of only 10% of the peak voltage of the preceding phase. Each phase had a duration of 5 ms, yielding a total shock duration of 15 ms.

However, a subsequent clinical study by Jung et al. was unable to show a significant advantage of triphasic over biphasic shocks [21]. In that study, biphasic and triphasic shocks were compared at an equal total shock duration of 10 ms. Because waveforms were possibly tested at non-optimal total shock durations, a hypothetical benefit of triphasic shocks might have been overlooked. Similarly, two experimental studies using a transthoracic defibrillation model were not able to observe a DFT reduction for various differently shaped triphasic shocks [27-29]. Again, the shock duration was not adjusted to an optimum setting, which might have influenced these multiple waveform comparisons. The waveform duration has a major impact on the efficacy of defibrillation shocks and varies for differently configured biphasic waveforms [9,11].

In the present study, we therefore systematically varied the total shock duration of biphasic and triphasic shocks in order to determine the optimal waveform-specific impulse duration with the lowest DFT for each waveform. We observed that shock-duration curves for triphasic defibrillation waveforms resemble inversely bell-shaped curves and are similar to shock strength-duration curves of monophasic and biphasic shocks. Strikingly, triphasic shocks consistently yielded higher DFTs when compared to biphasic shocks at the same duration. Even when both waveforms were compared at their optimal shock duration, biphasic shocks defibrillated at significantly lower shock voltages than triphasic ones. Specifically, the large voltage differences between biphasic and triphasic DFT raises the question of whether the shape of the triphasic waveform per se (i.e., the ratio of the phase durations and/or voltage amplitudes of the three phases) may have been responsible for the worse performance of triphasic shocks as compared to the biphasic shocks in our experiment.

Comparing our results with observations made by Huang and Ideker [22], it seems that besides waveform duration, the ratio of the phase amplitudes of triphasic shocks may play a crucial role for the defibrillation efficacy. These authors applied shocks with a high-amplitude first phase and a smaller-amplitude second and third phase. Using such triphasic waveforms, the authors demonstrated a slightly lower DFT for triphasic shocks as compared to biphasic shocks. In view of the substantial influence of total waveform duration on triphasic defibrillation efficacy as observed in our study, the defibrillation efficacy of triphasic shocks might even have been higher if these authors would have tested their specific triphasic waveform after optimization of total waveform duration. This certainly warrants further attention, as it may offer an additional opportunity to reduce defibrillation energy requirements with specifically shaped triphasic shock waveforms.

Conclusion

Shock strength-duration curves for triphasic defibrillation shocks resemble inversely bell-shaped curves and are similar to the shock strength-duration curves of biphasic shocks. Biphasic and triphasic shocks have defibrillation threshold minima at different shock durations, which must be accounted for when comparing the defibrillation efficacy of both waveforms. At optimized total shock durations, the defibrillation threshold for triphasic shocks with a large-amplitude second phase and a low-amplitude first and third phase is significantly higher than for biphasic shocks.

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