Can an RC Membrane Model Predict the Efficacy of a Defibrillation Waveform: An Analysis of Defibrillation Mechanisms in 140 Defibrillation Waveforms

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Abstract

Different defibrillation waveforms exhibit different efficacies. It has been proposed that a resistor-capacitor (RC) model of the myocardial membrane can explain these differences. Both the maximum capacitor voltage (charge banking) and the remaining voltage after the pulse (charge burping) have been proposed as efficacy predictors. Here, we test these hypotheses against 140 defibrillation waveforms. METHODS Data is reported from 159 guinea pigs. Each testedwaveform we calculated to within a fixed constant the minimum and maximum voltage on the capacitor, and the voltage remaining after the shock for time constants (τ) between 0.1 ms and 4.0 ms. Each parameter was tested to determine if it would be predicted to have a 10% impact on defibrillation efficacy. RESULTS No parameter was a significant predictor of defibrillation efficacy for τ>2.0ms. The maximum voltage was significant for short time constants (τ <=2.0 ms, p<0.005). For the very short time constants (<=0.5 ms) the voltage remaining was significant (p<0.05). And for the shortest time constants (t=0.1 ms) the minimum voltage was a significant predictor (p<0.05).

1. Introduction

Different defibrillation waveforms exhibit different efficacies for the same amount of delivered energy. However, the mechanism by which the defibrillation waveform influences efficacy is largely unknown. There have been many proposed hypotheses, but testing these hypotheses is difficult because only a few waveforms are typically available for analysis. Here we test a hypotheses against 140 defibrillation waveforms. This is the first test of a defibrillation waveform hypothesis in a large sample.

2. Methods

Data is reported from 159 animals. Two voltage-controlled bipolar power sources served as an arbitrary waveform defibrillator with an output up to 400V/2A. Two 12mm metal electrodes were placed 40mm apart on opposite sides of the mid-sternal line for defibrillation. Conductive paste was used between the shaved skin and the electrodes.

We determined the ED50 (the shock strength with 50% successful rate) for a standard 7ms/2ms biphasic waveform. Each animal received twenty shocks; 18 test waveforms, a fixed 9 ms monophasic and the 7/2 ms biphasic. A total of 140 waveforms were tested. All test shocks were given at the biphasic ED50.

Many authors, both recently, and in the past have proposed versions of the charge burping/banking theory [1]. The essential element of this hypothesis family is that the efficacy of a defibrillation waveform is related to the charge on the cell membrane due to the shock as calculated with a resistor-capacitor (RC) model of the membrane. The difference between the various hypotheses is their emphasis on the maximum or minimum charge during the shock [1], [2] or the charge left after the shock [3].

In order to test these hypotheses, we calculated the final, minimum and maximum charge on the membrane. The charge on the membrane at the end of any 1 ms time period i, was calculated as $C*V_{ci}$, where C is the membrane capacitance and V_{ci} is the voltage at the end of the time period. In this work, C was assumed to be constant. The voltage at the end of time period i was calculated as $V_{ci} = V_{c(i-1)} - (V_{c(i-1)} - KV)e^{(-1/\tau)}$, where $V_{c(i-1)}$ is the voltage at the end of the previous interval (or zero for the first interval), V is the voltage of the defibrillator during period i, K accounts for the drop in voltage between the defibrillator and the cell membrane, and τ is the time constant of the tissue (also called the RC time constant). K was assumed constant.

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The RC time constant was taken to be 0.06, 0.125, 0.25, 0.5, 1, 2, 3 and 4 ms. Each of these time constant possibilities was tested as a separate hypothesis.

3. Results

We found that the charge left on the capacitor was not a significant predictor of defibrillation efficacy for any values of τ in this range. The maximum charge parameter exhibits a maximum in correlation ($r=0.525$) for a τ of 0.5 ms. Nevertheless, the model is predicted to have a 10% impact on efficacy for time constants up to 2.0 ms ($p=0.04$). The minimum charge on the RC-modeled membrane is not predictive for any value of τ between 2 and 4 ms.

Very short time constants ($\tau<2$ ms) are not typically considered physiologic. However, the time constant of cardiac tissue for defibrillation may differ from that of normal physiology. Since our calculations lead to the calculated charge approaching the delivered voltage as the time constant shrinks, it is not surprising that the minimum charge is predictive of efficacy for short time constants ($\tau<0.5$ ms, $p<0.01$) as well as the maximum charge ($\tau=0.06$-1.0 ms, $p<0.001$). A more surprising finding is that for $\tau < 0.5$ ms, the charge remaining (which approaches the final stimulus voltage) is a significant predictor of defibrillation waveform efficacy ($p=0.026$).

4. Discussion

Several authors have proposed that the charge deposited on, removed from, or remaining on the cell membrane is the best predictor of the success of a defibrillation waveform. Our results might appear, at first, to suggest that these approaches are able to predict the efficacy of a defibrillation pulse to some extent, since they were predictors when the time constant was assumed to be very short ($\tau<0.5$ ms). However, this is probably not true because such time constants are shorter than the selected time resolution of our pulses. For such short time constants, the calculated minimum, maximum and final charge deposited on the membrane does not, in fact, depend on the membrane characteristics, but depends directly on the minimum, maximum and final waveform voltage.

Thus, our data cannot be used to support a dependence on the maximum or minimum deposited charge for short time constants, independent of a dependence on the maximum or minimum stimulus voltage.

There are two exceptions to the above dismissal of the charge-based hypotheses. The maximum deposited charge was a significant and independent predictor of the efficacy of a defibrillation waveform for time constants up to 2.0 ms. While this is a time constant shorter than typically assumed, it is longer than our temporal resolution. This result indicates that the deposited charge is a predictor of efficacy.

The second exception is the charge remaining on the cell. As the time constant is reduced, this approaches the magnitude of the final phase of the waveform, not the maximum and minimum of the waveform. The charge remaining for a very short time constant ($\tau=0.06$) was a strong negative predictor of efficacy. In other words, our data suggest that lower the final voltage of the waveform the higher the efficacy.

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