Systematic evaluation of the determinants of defibrillation efficacy

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OBJECTIVES We studied the effect of varying shock capacitance, shock impedance, and pulse duration on defibrillation efficacy in a randomized, crossover manner for biphasic shocks.

BACKGROUND The relationship between the electrical determinants of defibrillation efficacy is incompletely understood.

METHODS Biphasic shocks were delivered to 12 dogs through epicardial patches (to vary impedance) after 15 seconds of ventricular fibrillation using one of 100- or 155-μF capacitors at each of four pulse durations (2.5, 5, 10, 20 ms), in a balanced random order. There were two impedance groups: six with higher impedance (mean 97 $\pm$ 15 Ω, range 80–120) and six with lower impedance (mean 39 $\pm$ 3 Ω, range 34–44). Voltage requirements were estimated as the average of three defibrillation threshold (DFT) tests.

RESULTS Shock capacitance, resistance, and pulse duration all had significant effects upon the minimum voltage DFT ($P = .0065$, $P = .0066$, and $P = .0001$, respectively). The tilt associated with the lowest voltage and current requirement for each of the four capacitance/resistance combinations varied widely, between 34 $\pm$ 5% and 63 $\pm$ 3%, depending on capacitance and impedance. The optimal pulse duration associated with minimum DFT lies between 5.11 and 5.34 ms.

CONCLUSIONS Defibrillation voltage requirements for biphasic shocks are affected by pulse duration, capacitance and impedance, but not "tilt."

KEYWORDS Defibrillation; Electrophysiology; Tachyarrhythmias

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Introduction

Successful defibrillation from ventricular fibrillation requires shocks of sufficient strength to result in a minimum voltage gradient in most, if not all, of the fibrillating myocardium.[1] However, in the clinical setting, the effect of modifiable or programmable variables influences the probability of successful defibrillation. To maximize the efficiency and safety margin of defibrillation from implanted cardioverter-defibrillators (ICDs), the relationship among the defibrillation voltage requirement, shock pulse duration, device capacitance, tilt, and shock impedance must be understood. Although many investigators have examined the relationship between some measure of shock efficacy and pulse duration or capacitance,[2–5] no study has systematically varied these variables in conjunction with shock impedance for the biphasic shock waveform currently used in ICDs.

Understanding these relationships takes on a practical significance because different ICD manufacturers have taken different approaches to the problem of how to maximize the shock efficacy by varying defibrillation pulse duration. Some manufacturers specify a particular pulse "tilt" (the proportional decline in voltage during the pulse), which is assumed to lead to the most efficient use of the energy stored on the ICD's capacitors. Some manufacturers have fixed "tilt" devices and allow no duration programming, whereas others allow for programming true pulse durations, resulting in variable "tilts."

The advantages of specifying "tilt" compared to programming pulse duration, with respect to defibrillation efficacy, is not known. We hypothesized that the most useful measure of defibrillation efficacy for biphasic shocks, with respect to programmable parameters, would be peak initial

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voltage and that there would be no ideal "tilt." Rather, the voltage associated with the lowest defibrillation "threshold" would vary depending on the capacitors used, the shock impedance, and pulse duration. Therefore, we studied the effect of varying shock capacitance, shock impedance, and pulse duration on defibrillation voltage requirements for biphasic shocks in a randomized, crossover study in dogs. We also attempted to identify an optimal pulse duration at which defibrillation voltage requirements are minimized.

Methods

The experiments were approved by the St. Michael Hospital Animal Care Committee and conformed to the guidelines of the Canadian Council on animal care. In 12 mongrel dogs, anesthesia was induced with pentobarbital (30–35 mg/kg body weight IV) and maintained with a continuous infusion of pentobarbital at a rate of approximately 0.05 mg/kg/min.[6,7] The animals were intubated with a cuffed endotracheal tube and ventilated with 40% oxygen through a Harvard respirator (Harvard Apparatus, Inc., Holliston, MA, USA). A femoral arterial line was placed for hemodynamic monitoring and for arterial blood gas analysis and electrolyte measurements. Body temperature was maintained with humidified warmed gas in the ventilator circuit, and blood gases were measured every 90 minutes. The ventilator settings were adjusted as necessary to maintain oxygen, carbon dioxide, and pH in the physiologic range.

Through a left thoracotomy, two 12.5-cm^2 rectangular epicardial defibrillating patches (Telectronics, Inc., Englewood, CO, USA; n = 6) or one 12.5-cm^2 patch and an 8-cm^2 circular patch (Ventritex, Inc., Sunnyvale, CA, USA; n = 6) were sewn on the left lateral ventricle and the right ventricular outflow tract, respectively, in order to vary shocking lead impedance. Two epicardial screw in electrodes were attached to the left ventricle for induction of ventricular fibrillation (VF). After 15 minutes of stabilization, VF was induced using 60-Hz, 10-V impulses. Defibrillation test shocks were applied after 15 seconds of VF using a custom external defibrillator with programmable capacitance, stored voltage, and pulse duration (Telectronics). All shocks were biphasic, with 60:40 pulse duration ratio (3:2 ratio of first- to second-phase duration) and the leading edge of the second phase equal to the trailing edge of the first phase. The shocks were delivered with one of 100-or 155-μF capacitors at each of four total pulse durations (2.5, 5, 10, 20 ms) for a total of eight test conditions. The combination of one large/one small patch and two large patches was designed to produce "high" and 'low" shock impedance val-

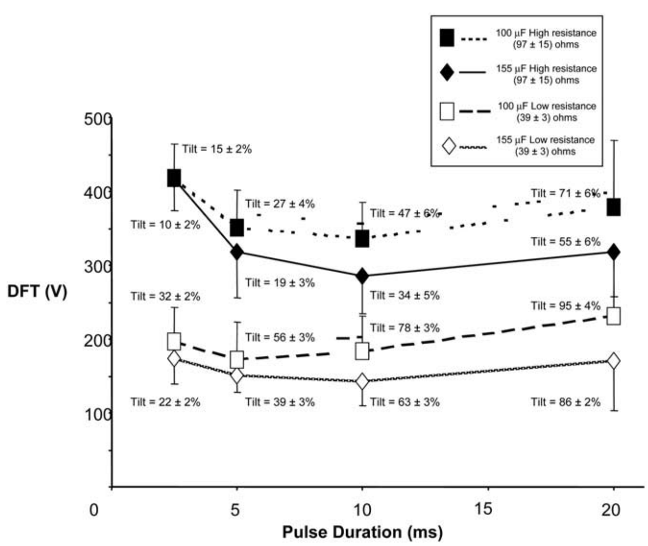

Figure 1 Defibrillation threshold (V_{50}) expressed as mean peak voltage ± SD for different pulse durations (in milliseconds) for four different experimental groups. The associated mean % tilt ± SD expressed as % decline of voltage during each pulse combination is illustrated. Pulse duration refers to the total pulse duration, including both phases.

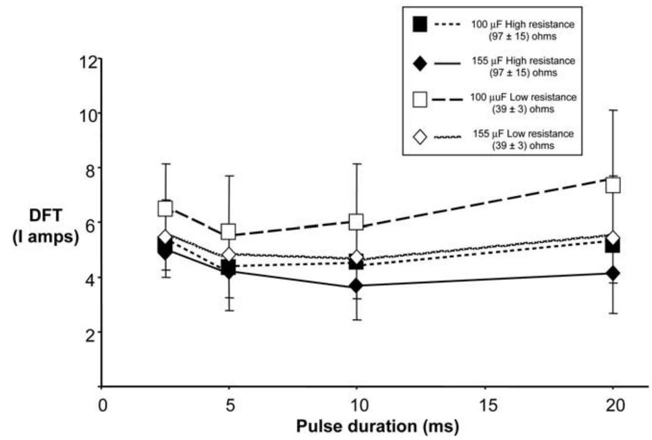

Figure 2 Defibrillation threshold (I_{50}) expressed as mean current ± SD for different pulse durations (in milliseconds) for four different experimental groups.

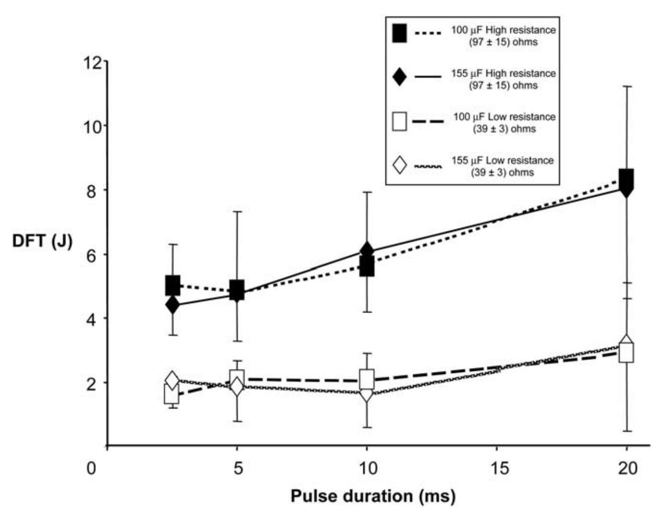

Figure 3 Defibrillation threshold (E_{50}) expressed as mean delivered energy ± SD for different pulse durations (in milliseconds) for four different experimental groups.