Editorial

Is there an optimal capacitance for defibrillation?

All implantable cardioverter-defibrillators (ICDs) contain a capacitor, which is an electronic component that can store electric charge. While capacitors come in many sizes and shapes and are constructed of different materials, essentially they all consist of two conductors separated by an insulator. When a capacitor is connected to a battery, electrons flow to the conductor in the capacitor attached to the cathode of the battery. The anode of the battery attracts electrons away from the other conductor in the capacitor. Thus, the first conductor acquires a net negative charge while the second conductor acquires a net positive charge of equal magnitude. When the battery is disconnected, these electrical charges of opposite polarity, separated by the insulator, are stored until the conductor is connected by a conducting path. After the connection is made, electrons pass from the negatively charged conductor through the conductive pathway to the positively charged conductor.

The energy required to defibrillate is much greater than can be delivered directly from ICD batteries during the few milliseconds of a shock. By connecting an ICD battery to a capacitor for several seconds, the capacitor can be charged to a high energy level and then rapidly deliver the charge as a shock. The rapidity with which the capacitor delivers its charge to a patient depends on the capacitance (C) and the resistance (R). Capacitance is a measure of the amount of charge that the capacitor can store for a given voltage, while resistance is a measure of the impedance to current flow in the discharge circuit, which consists primarily of the ICD leads and the patient’s body. The time for the capacitor to discharge increases with increases in either R or C. This time is quantified by the time constant (τ), the amount of time required for the capacitor to discharge sufficiently to decrease the voltage across it by 63%, which is equal to the product of R and C. When C is expressed in farads (the capacitance of a capacitor which stores one coulomb of charge [6.24 × 10^18 electrons] with a 1 volt difference across the capacitor) and R is given in ohms (1 ohm [Ω] causes a current of 1 amp [1 coulomb per s] when 1 volt is applied across the resistance), τ will be in seconds. As the capacitor discharges through a fixed resistance, the voltage across the capacitor decreases exponentially with time.

In addition to τ, there are several other variables associated with the ICD capacitor or the waveform it generates that have clinical significance, since they influence the likelihood that the shock will succeed in halting fibrillation. Some of these variables are the stored voltage across the capacitor, the stored energy in the capacitor, and the delivered energy to the patient when the capacitor is discharged during the shock. The delivered energy is less than the stored energy, because the capacitor is not allowed to discharge fully during the shock. Rather, the shock waveform is truncated by switching off the capacitor before it is fully discharged. The tilt of the shock waveform is defined as the difference between the shock voltage when the shock is turned on (the leading-edge voltage) and when the shock is turned off (the trailing-edge voltage) divided by the leading-edge voltage. For example, the tilt of a waveform whose duration is equal to τ is 63%. In addition to tilt, other important variables affecting defibrillation efficacy are the number of phases of the waveform and the duration of each phase of the waveform. All of these variables are not independent. The stored energy can be calculated from the capacitance and the stored voltage (V): $E = \frac{1}{2}CV^2$. Waveform tilt can be calculated from τ and the waveform duration (d): $t_{ilt} = 1 - e^{-d/\tau}$, where $e = 2.72$.

What is the optimal capacitance for the ICD? The answer to this question depends upon which quantity is chosen to be optimized. There are at least five quantities that can be optimized by finding the capacitance for which the quantities are a minimum: (1) the voltage required for defibrillation, (2) the energy required for defibrillation, (3) detrimental effects caused by the shock, (4) the size of the ICD, and (5) the amount of time necessary to charge the capacitor. In presently available ICDs this last variable, which partially determines the duration of fibrillation before the shock is given, is directly related to the stored energy independent of the capacitance, since constant power charge circuits are used.

Many experimental studies in animals and humans have been performed to answer these questions. In
most of these studies the efficacies of the different waveforms have been ranked based on their ability to minimize the delivered energy. From these experimental results, investigators have derived relatively simple equations to predict the efficacy of different waveforms and of different capacitances\cite{3-7}. These models predict that a capacitance of 90 μF or even less should be superior to the 140–150 μF capacitance that is standard in ICDs because they should require less energy when a short duration waveform is used. While a smaller capacitance (60 μF) does not defibrillate with lower energy than a 120 μF capacitance when the lead resistance is low (≤40 Ω), it requires less energy to defibrillate when the lead resistance is high (>60 Ω)\cite{8}. However, defibrillation with smaller capacitance requires significantly more voltage, even though the energy is the same or moderately decreased, since according to the equation given above a smaller C requires a larger V for the capacitor to contain the same amount of energy. Since some evidence suggests that detrimental effects of shock, such as electroporation, are more closely related to peak shock voltage than shock energy\cite{9,10}, these shocks from ICDs with a smaller capacitance may be more likely to cause damage, even though they are the same or slightly lower energy than shocks from ICDs with a standard size capacitance.

Other investigators have taken the opposite approach and have experimentally evaluated larger capacitors of 336–500 μF\cite{11,12}, which models indicate should decrease the voltage required for defibrillation. The most recent of these studies is that by Brugada et al.\cite{13} in this issue of Europace\cite{13}. These studies found that, while the larger capacitors markedly reduced the voltage required for defibrillation, they either did not significantly change or only slightly increased the energy required for defibrillation. In the study by Brugada et al.\cite{13}, a biphasic waveform delivered from a 336 μF capacitor with a total tilt of 60%, in which the first phase was 60% of the total waveform duration, required significantly lower energy for defibrillation than did an 80% tilt biphasic waveform delivered from a 140 μF capacitor with the first phase 60% of the total waveform duration.

A 336 μF capacitor was used in the study by Brugada et al. because it consisted of only a single physical capacitor. The standard 140 μF capacitor, as well as the smaller capacitors discussed above, physically consist of two or more capacitors connected in series. Standard capacitors used in ICDs cannot be charged to voltages greater than approximately 390 volts, which is not enough energy to defibrillate for a capacitance of 140 μF or less. Since the total voltage output of capacitors in series is equal to the sum of the voltages of each of the capacitors, it is necessary to connect two or more capacitors in series to provide sufficient voltage and energy for defibrillation. A voltage of 390 V across a 336 μF capacitor stores 26 J which, in the study by Brugada et al., was sufficient to provide a 10 J safety margin for all patients, since no patient had a defibrillation threshold higher than 15 J with the 60% tilt waveform delivered from the 336 μF capacitor.

According to Brugada et al.\cite{13}, use of a single 336 μF capacitor instead of the two capacitors in series to create the 140 μF net capacitance in standard ICDs would save approximately 7 cc of space, which would allow the defibrillator to be smaller. However, newer types of capacitors have recently become available that occupy less space even when several are connected in series. In addition, before unequivocally accepting the results of this study and its implications for the optimal capacitance in ICDs, several limitations of the study must be considered, some of which are acknowledged by the authors.

One, the study was stopped early. Based on a power calculation performed before the beginning of the studies, each study was to have enrolled 41 patients. Yet, the first study was terminated after enrolling 33 patients and the second study after enrolling 21 patients, because significant differences between the two waveforms were already present. Statistically evaluating the tested variables several times during a study will increase the probability that a significant difference will be found by chance. While there are statistical techniques to compensate for analysing the data multiple times during the course of a study\cite{14}, there is no indication in the manuscript that the authors employed such techniques.

Two, the patients in the two studies appear to have been different. As can be seen in Fig. 2 of the paper by Brugada et al.\cite{13}, the mean reference defibrillation threshold for the shock from the 140 μF capacitor was different in the two studies. In fact, the defibrillation threshold for the 140 μF shock in the second group of patients was lower than the defibrillation threshold for the 336 μF shocks in the first group of patients, which was significantly lower than the defibrillation threshold for this same 140 μF capacitor shock in the first group of patients.

Three, the means and standard deviations of the resistance in the two groups, 43 ± 5 and 46 ± 5 Ω, suggests that there were few patients with a high resistance (>70 Ω). It is in patients with such high resistances that the high voltage shocks from a small capacitor would be most advantageous vs the lower voltage shocks from a large capacitor.

Finally, the left ventricular ejection fractions in the two groups, 44 ± 15% and 47 ± 15%, are considerably

Europace, Vol. 3, October 2001
higher than that in many earlier studies of patients with ICDs\textsuperscript{[15]}. The facts that the ejection fractions were high in the patients and few of the patients had high resistances may be responsible for the absence of any patient with a defibrillation threshold higher than 15 J in the study. Although no patients in this study had a defibrillation threshold higher than 15 J, it is likely that there will be patients who have a defibrillation threshold higher than 15 J for shocks delivered from the 336 μF capacitor. If so, and if a safety factor of at least 10 J is required, then an ICD with a 336 μF capacitor should not be used in these patients.

The quest for a tiny ICD is a laudable goal. However, the need for ICDs to be effective is paramount. Whether or not bigger or smaller is better depends on the entity being quantitated. Only if a bigger capacitor is equally or more effective than the currently used capacitor technology should it be incorporated into ICDs. On the other hand, if capacitors are less consistently effective, a smaller ICD size is not a service to patients.

Partially supported by NHLBI grants HL-42760 and HL-63795. Dr Ideker’s laboratory receives research funding from Guidant Corporation and Medtronic/Physio-Control. Drs Ideker and Walcott are consultants and Dr Epstein is an investigator for Guidant Corporation.

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References


