Effect of Duration of Ventricular Fibrillation on Defibrillation Efficacy in Humans

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The currently available automatic implantable cardioverter-defibrillator has proven highly successful for termination of ventricular tachycardia and fibrillation. Newer devices, however, permit lower energy shocks to be delivered initially and longer episodes of arrhythmia to occur before shocks are delivered. These changes may result in longer durations of arrhythmia before successful termination. Little is known about the effects of the duration of ventricular fibrillation on the efficacy of defibrillating shocks. In this study, we examined the efficacy of defibrillating shocks in 22 patients undergoing automatic implantable cardioverter-defibrillator implantation or generator change. Defibrillating shocks ranging from 300 to 600 V (5.9–24.2 J) were delivered in matched pairs after 5 and 15 seconds of ventricular fibrillation. For the 300-V shocks (5.9 J), defibrillation was accomplished in 82% of patients when the shocks were given after 5 seconds of ventricular fibrillation and in only 45% of patients when the shocks were delivered after 15 seconds (p<0.01). At higher energies, there was no difference in the efficacy of defibrillation shocks delivered after 5 compared with 15 seconds of ventricular fibrillation. The postshock aortic, systolic, and diastolic blood pressures were significantly lower when the shocks were given after 15 seconds of ventricular fibrillation than after only 5 seconds. We conclude that the duration of ventricular fibrillation affects defibrillation efficacy especially at energies that are relatively low compared with maximal device outputs and that longer episodes of ventricular fibrillation cause more postshock hemodynamic depression. These observations have implications for defibrillation threshold testing at the time of device implantation and for the design and programming of future automatic implantable antitachycardia devices. (Circulation 1990;81:1477–1481)

The only consistently effective therapy for ventricular fibrillation is the delivery of a timely defibrillation shock. This can be accomplished either transthoracically with an external defibrillator or with permanently implanted leads and the automatic implantable cardioverter-defibrillator. Although prompt defibrillation is generally considered necessary to prevent irreversible neurological damage, there is only a small body of data about the effect of the duration of ventricular fibrillation on the efficacy of defibrillating shocks. In dogs, the efficacy of defibrillation decreases as the duration of ventricular fibrillation increases for transthoracic shocks\(^1\) and for truncated exponential shocks by permanently implanted lead systems.\(^2\) In humans, the available data on transthoracic defibrillation are somewhat controversial. Some studies of cardiac arrest patients have shown that the duration of fibrillation is inversely proportional to the success of defibrillating shocks,\(^3\) whereas other studies have not found this relation.\(^4\)

All widely available implantable defibrillating devices to date have had factory preset sensing capabilities and have delivered only a fixed defibrillating energy. These devices are remarkably effective for terminating episodes of spontaneous and artificially induced ventricular tachycardia and fibrillation.\(^5\)–\(^7\) Newer devices, however, will permit the programming of lower and potentially ineffective initial energies. They will also permit programming of the duration of arrhythmia that must occur before therapy is delivered to avoid shocking nonsustained episodes of ventricular tachyarrhythmias. Although this programmability is considered beneficial for most patients, it may delay the delivery of lifesaving defibrillatory shocks. It is, therefore, important to understand the relation between the duration of ventricular fibrillation before

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Received May 12, 1989; revision accepted January 4, 1990.
shocks are delivered and the success of defibrillating shocks in terminating the arrhythmia. This study examines the efficacy of defibrillating shocks after 5 and 15 seconds of ventricular fibrillation with a lead system and waveforms similar to those of the present implantable defibrillator.

**Methods**

All patients in this study had a history of sustained ventricular tachycardia or fibrillation and were undergoing new automatic implantable cardioverter-defibrillator implantation or generator change for standard clinical indications. All patients signed written, informed consent, and the study was approved by the investigational review board of Sequoia Hospital. The study was performed as part of defibrillation threshold testing on these patients. All patients were under general anesthesia. Patients undergoing new implantation had their antiarrhythmic drugs withheld if possible, and those undergoing generator changes had long-term antiarrhythmic therapy continued. Arterial blood pressure monitoring was performed with a standard radial arterial catheter. Simultaneous recordings of surface electrocardiographic leads I, II, and III, electrograms from the shocking lead electrodes, electrograms from the local ventricular bipolar sensing leads, and recordings for the phasic arterial pressure were made with a recorder at 25 mm/sec paper speed (Electronics for Medicine, Pleasantville, New York). Ventricular fibrillation was induced in each patient with rectified alternating current by a temporary pacing catheter placed under fluoroscopic control at the right ventricular apex. Ventricular fibrillation was defined as a polymorphic ventricular rhythm with a cycle length shorter than 250 msec that resulted in no phasic blood pressure. Episodes of ventricular fibrillation were terminated with a Ventritex HVS-02 (Sunnyvale, California), which is capable of delivering truncated exponential waveforms of a specified initial voltage and duration. After a single test shock to measure shocking lead impedance, the pulse duration was chosen to simulate the waveform that would be delivered from the automatic implantable cardioverter-defibrillator generator (CPI).

Each patient participating in this study underwent eight separate episodes of ventricular fibrillation induction consisting of two separate tests with 300, 400, 500, and 600 V initial waveform voltage. For each initial waveform voltage, a shock was given after 5 seconds of sustained ventricular fibrillation during one episode of induced ventricular fibrillation, and an identical shock was given after 15 seconds of sustained ventricular fibrillation during the other episode. The order of testing of the four voltages was randomized for each patient and so was the order of testing of 5 and 15 seconds of ventricular fibrillation before the shocks were given. For each shock, the actual delivered energy and measured shocking lead impedance were determined from the HVS-02. For each successful shock, the systolic and diastolic blood pressures were recorded 5 seconds after the shock and so was the time to the first spontaneous QRS complex after termination of the ventricular fibrillation. Unsuccessful shocks were followed promptly by 600-V rescue shocks. For data analysis only, the data from the first shock for each of eight induced episodes of ventricular fibrillation were used.

All data are mean±SD. Student’s t test was used to compare the energy delivered, measured impedance, time to first spontaneous R wave, and systolic and diastolic blood pressures after 5 and 15 seconds of ventricular fibrillation. The success of defibrillation at each of the four voltage levels was compared after 5 and 15 seconds with χ² analysis.

**Results**

**Patient Population**

Twenty-two patients participated in this study; nine underwent new defibrillator system implantation and 13 underwent generator change. The average age was 52.2±14.2 years (range, 17–72 years). The average ejection fraction was 32.7±18.0% (range, 15–59%), and the underlying heart disease was coronary artery disease in 17 patients, cardiomyopathy in three patients, mitral valve prolapse in one patient, and right ventricular dysplasia in one patient. The shocking lead configuration was large patch–large patch in 17 patients, large patch–small patch in two patients, and spring–small patch in three patients. Fifteen patients were receiving no antiarrhythmic drugs, three were receiving quinidine, two were receiving procainamide, and one each was receiving sotalol and amiodarone. Other drugs taken included β-blocking drugs in five patients, digoxin in four patients, and verapamil in one patient.

**Energy Delivery and Impedance**

Table 1 shows the delivered energy and measured impedance after 5 and 15 seconds at each of the four voltages tested. As voltage increased from 300 to 600 V, delivered energy increased from 5.9 to 24.4 J. There were no significant differences between delivered energy after 5 and 15 seconds of ventricular fibrillation for any of the four voltages tested. There was a consistent trend toward a decreased impedance

<table>
<thead>
<tr>
<th>Energy level (V)</th>
<th>Time (sec)</th>
<th>Energy (J)</th>
<th>Impedance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>5</td>
<td>5.9±0.15</td>
<td>46.5±16.4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>5.9±0.26</td>
<td>46.2±16.9</td>
</tr>
<tr>
<td>400</td>
<td>5</td>
<td>10.4±0.86</td>
<td>44.5±15.3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10.6±0.19</td>
<td>44.5±15.6</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>16.7±0.59</td>
<td>43.7±15.0</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>16.7±0.28</td>
<td>43.1±14.8</td>
</tr>
<tr>
<td>600</td>
<td>5</td>
<td>24.1±1.5</td>
<td>42.6±15.1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>24.4±0.68</td>
<td>42.8±15.0</td>
</tr>
</tbody>
</table>
as voltage increased. There was, however, no significant difference in impedance after 5 compared with 15 seconds of ventricular fibrillation for any of the four voltages tested.

**Effect of Duration of Ventricular Fibrillation on Defibrillation Efficacy**

Figure 1 shows the percent successful defibrillations at each of the four energies for 5 and 15 seconds of ventricular fibrillation. For the 300-V shocks corresponding to 5.9 J, significantly more patients (82% vs. 45%, \( p < 0.05 \)) were defibrillated when the shock was delivered after 5 seconds (compared with 15 seconds) of ventricular fibrillation. For each of the higher voltages (400 V, 73% vs. 73%; 500 V, 86% vs. 82%; and 600 V, 90% vs. 76%), there was no significant difference in defibrillation efficacy when the shocks were given after 5 compared with 15 seconds of ventricular fibrillation.

![Percent Successful Defibrillation](image)

**FIGURE 1. Bar graph of percent successful defibrillation for each of the four voltage levels at 5 and 15 seconds of ventricular fibrillation. For 300 V, the defibrillation shocks were significantly more effective when delivered after 5 than after 15 seconds of ventricular fibrillation. For each of the three higher energy shocks, there were no significant differences in defibrillation efficacy between 5 and 15 seconds (see text).**

**NS, not significant.**

**Postshock Blood Pressure**

Table 2 shows the systolic and diastolic blood pressures for each of the four voltages tested 5 and 15 seconds after termination of the ventricular fibrillation. For each of the four voltages tested, systolic and diastolic blood pressures were lower after 15 seconds compared with after 5 seconds of ventricular fibrillation before successful termination. Blood pressures were significantly different for all voltages and pressures except the decrease in systolic blood pressure at 500 V (\( p < 0.13 \)). With regard to time to the first spontaneous QRS complex after successful defibrillation, there was no significant difference between 5 and 15 seconds of ventricular fibrillation (Table 3). Because atrial electrograms were not recorded, it was not possible to determine whether the first postshock QRS complexes were sinus.

**Discussion**

Most previous studies examining the effect of the duration of ventricular fibrillation on defibrillation efficacy were conducted in closed-chest models. Out-of-hospital studies indicate that the duration of cardiac arrest before the initial defibrillation shock and the presence of “fine” ventricular fibrillation both result in decreased defibrillation efficacy and hospital discharge rates. In a study of cardiac arrest at a university hospital, Kerber and Sarnat found that...
the duration of ventricular fibrillation before the initial shock, acidosis, and hypoxia were significant factors in determining successful defibrillation. In 94 patients undergoing in-hospital defibrillation for cardiac arrest, Gascho et al. however, did not find that time before the first defibrillation shock was an important factor in determining successful defibrillation. Using a canine model of transthoracic defibrillation, Yakaitis et al. found the success of defibrillation was inversely proportional to the duration of ventricular fibrillation, with times ranging from 1 to 9 minutes. In that study, the curves comparing percent successful defibrillation with energy delivered reached a plateau at percent success rates well below 100% for the longer durations of ventricular fibrillation; this suggested that successful defibrillation may not always be achieved even when extremely high energies are used.

Tacker et al. using a transvenous defibrillation catheter in dogs, showed there was no change in defibrillation thresholds with durations of ventricular fibrillation ranging from 10 to 40 seconds. Echt et al. however, did show an effect of the duration of ventricular fibrillation on defibrillation threshold in dogs with a transvenous catheter–subcutaneous patch electrode system and single truncated exponential waveforms. The energy required to achieve 90% successful defibrillation after 5, 15, and 30 seconds of ventricular fibrillation was 27±13, 36±17, and 41±14 J. These data did not include four animals that could not be defibrillated after 30 seconds of fibrillation despite the use of higher energy internal shocks and external shocks up to 320 J. Bardy et al. suggested that in humans subthreshold sequential waveform pulses given with the 6880 catheter and the Epicardial TX-7 lead (Medtronic, Minneapolis, Minnesota) increase the energy requirements for later rescue shocks by 61%. The time difference between the initial defibrillation threshold pulses and the rescue pulses was 12.4±3.5 and 28.0±6.2 seconds. This time delay rather than the previously unsuccessful subthreshold shock may have accounted for the increased energy requirements for defibrillation. Platia et al. reported preliminary data in humans with standard automatic internal cardioverter-defibrillator leads and monophasic truncated exponential waveforms that indicated that defibrillation threshold increased from 7±4 to 23±8 J as the duration of ventricular fibrillation increased from 5 to 25 seconds.

The present study shows that for energies that are relatively low compared with the 25–30-J output of the present implantable cardioverter-defibrillator, it is more difficult to defibrillate after 15 than after 5 seconds of ventricular fibrillation. Our data suggest that for periods of ventricular fibrillation up to 15 seconds the effect on defibrillation threshold of increasing time can be overcome by delivering higher energy shocks. The data suggest that there is no single value of defibrillation threshold but that this is a dynamic variable depending on the conditions under which it is measured. Our data also indicate that there is more hemodynamic depression (manifest by a lower systemic blood pressure) after termination of longer episodes of ventricular fibrillation.

The findings of this study have several important clinical implications. The present automatic implantable cardioverter-defibrillator requires approximately 5–15 seconds to sense ventricular fibrillation and another 6–8 seconds to deliver a 25–30-J output. The elapsed time of ventricular tachycardia or fibrillation before shock delivery is in the 13–18-second range for most patients. When performing intraoperative defibrillation threshold evaluations, one would like to obtain the maximum amount of data relative to device efficacy with the least risk to the patient. Many patients have poor left ventricular function and can be subjected to only a moderate number of fibrillation-defibrillation sequences. Our data suggest that if patients have defibrillation thresholds that are low compared with the output of the generator to be implanted, then relatively short durations of induced ventricular fibrillation will be sufficient to demonstrate device efficacy with the least hemodynamic depression. If defibrillation thresholds are high relative to maximum device output, it is important to use longer durations of ventricular fibrillation.

Implanted devices are now available that may be programmed to low-energy initial shocks and in which the duration of the arrhythmia before capacitor charging is programmable. Charge times to achieve low-energy shocks are significantly shorter than those required to charge to full output. Our data indicate that low-energy shocks delivered earlier during an episode of ventricular fibrillation may be more efficacious than the same shock or even higher energy shocks given later in an episode. Conversely, shocks given late during an episode may be less efficacious than similar shocks given early in an episode. For patients with marginal defibrillation thresholds compared with maximum defibrillator generator output, devices should be programmed to avoid excessive delays in arrhythmia sensing or termination lest defibrillation threshold exceed maximum device output.

The data in this study represent only group averages. It is quite likely that an occasional individual patient might be extraordinarily sensitive to the duration of fibrillation. For this reason, after completion of defibrillation threshold testing with short durations of fibrillation, all patients should undergo one or more defibrillation attempts after longer durations of ventricular fibrillation similar to those that will occur on a clinical basis. Our data probably represent the worst case, because we initiated ventricular fibrillation with rectified alternating current and because all patients were in ventricular fibrillation for the entire duration of their arrhythmia episode. However, the spontaneous arrhythmia episodes of most patients begin as ventricular tachycardia or flutter, and these are usually the arrhythmias present at the time the initial shock is delivered.
Ventricular tachycardia is generally more easily terminated with lower energy shocks than is ventricular fibrillation.\textsuperscript{13}

Our data should not be extrapolated beyond the 15-second duration of ventricular fibrillation that we evaluated. The difference in defibrillation efficacy between 5 and 15 seconds seen only at 300 V in this study could possibly be observed at higher energies if the duration of fibrillation is longer than 15 seconds. Also, in some patients, longer duration of ventricular fibrillation could possibly result in an inability to defibrillate with any energy.

Although it could be argued that all defibrillation efficacy testing in patients should be done with 15–25-second episodes of ventricular fibrillation, we do not believe that the information learned justifies the additional risk associated with repeated longer fibrillation-defibrillation episodes that result in significant hypotension after the termination of the episodes of arrhythmia. Extensive clinical experience\textsuperscript{5} based on routine use of 5–10 seconds of induced ventricular fibrillation for defibrillation threshold testing at the time of defibrillator implantation has resulted in an extraordinarily small number of patients dying suddenly during long-term follow-up. Thus, patient safety considerations and common sense argue in favor of using short durations of ventricular fibrillation for routine defibrillation threshold testing in most patients.

Acknowledgments

We thank Drs. Thomas Fogarty and Duncan Mason for their surgical assistance; the physicians, physician assistants, and nurses at Sequoia Hospital who participated in the care of these patients; David Ahn for statistical consultation; and Glenda Rhodes for secretarial support.

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Circulation. 1990;81:1477-1481
doi: 10.1161/01.CIR.81.5.1477

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