Prediction of Defibrillation Success From a Single Defibrillation Threshold Measurement With Sequential Pulses and Two Current Pathways in Humans

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The ultimate aim of defibrillation testing is to predict consistent defibrillation. This study tested the hypothesis that defibrillation success could be predicted from a single measurement of defibrillation threshold. We measured defibrillation threshold by using three patch electrodes and a standard protocol intraoperatively in 49 patients undergoing arrhythmia surgery. Each patient was then assigned to one of five energy subgroups (0.5, 1.0, 1.5, 2.0, or 2.5 times defibrillation threshold) for a single shock (followed by a rescue shock if necessary) for a subsequent ventricular fibrillation episode. A curve relating percent success to energy was then constructed for the group. Defibrillation threshold averaged 4.7 ± 2.98 J for the group (mean ± SD). There was a curvilinear relation between the energy of the defibrillation threshold ratio test shock and percent success: 33.3%, 58.3%, 81.8%, 91.7%, and 100% at mean defibrillation threshold ratios of 0.56 ± 0.14, 1.02 ± 0.07, 1.53 ± 0.14, 1.88 ± 0.09, and 2.60 ± 0.14, respectively. We conclude that consistent defibrillation is predictable from a single measurement of defibrillation threshold. Furthermore, for an individual patient, a safety margin of 2.6 times defibrillation threshold should approximate 100% successful defibrillation for a single test shock. (Circulation 1988;78:1144–1149)

Implantation of an automatic defibrillation device necessitates an estimate of the energy requirements for defibrillation to ensure that the device will defibrillate consistently at its maximum output. In experimental animals, many defibrillation attempts may be performed, and the relation may be plotted between percentage of successful defibrillation and defibrillation energy delivery.1–3 In patients, the number of defibrillation episodes is limited, and defibrillation threshold is a more readily attainable measure.4–6 The purpose of this study was to evaluate how a single defibrillation threshold could be used to estimate a margin of safety for successful defibrillation and to provide “acceptable and unacceptable” criteria for a specific lead system and device.

Patients and Methods

Patient Population

Fifty-one successive volunteer patients undergoing arrhythmia surgery (33 men and 18 women) provided written and verbal, informed consent in accordance with the regulations of the Health Sciences Standing Committee on Human Research of The University of Western Ontario, London, Ontario, Canada. The mean age was 31.7 ± 9.4 years (range, 19–54 years) with mean weight 73.4 ± 13.5 kg (range, 51.1–109.6 kg). Patients were randomized to one of five test-energy subgroups (0.5, 1.0, 1.5, 2.0, or 2.5 times defibrillation threshold).

Surgical Procedure

Patients were prepared for surgery, and the heart was exposed by a median sternotomy. The heart...
After a minimum ventricular fibrillation of 10 seconds, defibrillation was attempted. The defibrillation threshold was determined as follows. The initial defibrillation setting was at a stored voltage of 300 V, which corresponded to an estimated energy delivery of approximately 3 J. Subsequent shocks in the fibrillation episode were at increments of approximately 1 J for shocks up to 10 J, then at increments of 2.5 J for shocks up to 15 J until defibrillation was successful. If the first shock of a fibrillation episode was successful, an additional episode was allowed that started at a stored voltage of 170 V, which corresponded to a calculated energy delivery of approximately 1 J. Increments of 1 J were used until defibrillation was successful. Defibrillation threshold was defined as the minimum energy required to cause defibrillation.

Once defibrillation threshold had been determined, estimated stored voltage for a test shock was calculated, which would correspond to that necessary to deliver the randomly selected ratio of defibrillation threshold energy for that patient. The initial stored voltage was set at the test shock voltage level. Ventricular fibrillation was induced after 5 minutes, and the defibrillation test shock was delivered and was followed immediately by rescue shock if necessary. A maximum of three ventricular fibrillation episodes, each separated by 5 minutes, were allowed. The total potential duration of circulatory arrest for all fibrillation episodes in a single patient averaged 44.8±12.4 seconds (range, 29–71.5 seconds).

Energy Delivery Determination

Scaled output waveforms from the defibrillators were delivered to an analog-to-digital converter mounted in a portable personal computer. The computer program allowed on-line display of waveforms immediately after the delivery of a shock, and after successful defibrillation, it permitted determination of the peak voltage, peak current, impedance, duration of each pulse, energy delivery from each pulse, and total delivered energy for every shock. Energy was calculated by the integrated area under the curve and the correction for the logarithmic decay of the capacitive discharge.

Statistical Analysis

Analysis of the difference in the total energy, leading edge peak voltages, and currents for each energy ratio was made by analysis of variance. Data are presented as the mean ± SD. A probability of 0.05 or less was considered significant.

Results

Two patients were not included in the analysis because of technical problems. The remaining 49 patients had defibrillation thresholds determined and were administered one of the five energy ratio test shocks. Defibrillation threshold for the 49 patients averaged 4.7±2.9 J.
predominance of unsuccessful shocks fell below the defibrillation threshold, whereas most successful shocks were with ratios equal to or greater than the defibrillation threshold.

Mean peak voltages for the first and second pulse of the test shock ranged from approximately 200 to 450 V (Figure 3). There was a slight diminution in the peak voltage of those patients receiving more than a 2.25 times defibrillation threshold. This was due to the inaccuracy of calculation of the defibrillation threshold ratio and to not attempting to correct stored voltage of the test shock for different impedances. These inaccuracies were greatest in those patients in whom defibrillation threshold was approximately 1–2 J. This resulted in more patients with low defibrillation threshold in the highest group.

The corresponding mean peak current of these test shocks was from 2.5 A to a maximum of approximately 6.5 A. There was a slight diminution in the mean peak current for the patients receiving greater than 2.25 times defibrillation threshold ratio (Figure 4).
The resultant calculated mean delivered energy of the test shocks ranged from approximately 2 J for the lowest ratio to a maximum of approximately 9.5 J for the maximum total energy delivered (Figure 5). Of note, this total energy was delivered to two different pathways. Thus, the delivered energy through each pathway was one half of the total (Figure 5).

Defibrillation threshold for the 49 patients averaged 4.7 ± 2.9 J. There was a difference noted depending on the particular electrode configuration. The average defibrillation threshold for the coil electrode configuration was slightly, but significantly, lower than that of the mesh electrode configuration (Figure 6).

A curve relating the percentage of successful defibrillation to test shock–delivered energy was constructed for the group (Figure 7A). When plotted as a log of the defibrillation threshold ratio, the plot was linear and ranged from approximately 35% at 0.5 times defibrillation threshold to 100% at approximately 2.6 times defibrillation threshold. After having determined that defibrillation threshold with the coil configuration was slightly lower than that of the mesh electrode configuration, we replotted data with only test-shock data from patients with the coil electrodes (Figure 7B). By this method, the plot had a plateau with 100% successful defibrillation between 2.0 and 2.5 times defibrillation threshold. Again, the plot was linear between the minimum of approximately 35% at the 0.5 times defibrillation threshold and 100% at 2.0 times defibrillation threshold. Of note, these curves are constructed from the first shock only of the test sequence and therefore are the percent success of the first shock of the new fibrillation episode.

Discussion

This study demonstrates that defibrillation in humans can be consistently achieved with threshold energy averaging 4.7 J with coil and mesh electrode systems. These results are consistent with our previous studies in animals and humans in which we found low thresholds with patch electrodes and sequential pulse technique for defibrillation.12–14

For patients receiving an implanted automatic defibrillator, it is essential to estimate the energy necessary for consistent defibrillation and to predict the safety margin available for a specific lead system and device. Several methods have been suggested for such determinations.2–4,15–18 However, with patient studies, it is not reasonable to have a large number of defibrillation episodes. On the other hand, a single defibrillation threshold determination is rapid, easy to obtain, and, thus, more

![Figure 5](http://circ.ahajournals.org/)

**Figure 5.** Bar graphs of mean values for test shock–delivered energy for the first (Panel A) and second (Panel B) pulses and total shock (Panel C). End bars represent ±SD. Numbers of patients in each group from left to right are 6, 12, 11, 12, and 8, respectively.

![Figure 6](http://circ.ahajournals.org/)

**Figure 6.** Bar graph of means of total delivered energy at defibrillation threshold for all patients that had current delivered through coil (n=35) or mesh (n=14) electrodes. End bars represent ±SD. Differences between the two means, although small, are statistically significant (t = -2.43, p < 0.05).
feasible considering the restrictions of the operating room environment. This study suggests that a single measurement of defibrillation threshold can be used to predict successful defibrillation from the first shock of subsequent ventricular fibrillation episodes under similar circumstances in the same patient.

In this study, 2.6 times defibrillation threshold achieved 100% successful defibrillation with the first shock. Of note, the shape of the curve between percent success and the defibrillation threshold ratio depended on the particular electrodes used. This suggests that in addition to surface area of electrodes, the efficiency of a particular electrode system may also be important in determining the shape of a curve of percent success and defibrillation threshold ratio. Direct cardiac shocks with single-pulse current delivery with either intravascular catheters or an epicardial system have been successful in humans when energies range from 15–35 J and when there is a relatively shallow slope for the dose-response curve. In the present study, the slope was relatively steep, and the maximum threshold with the coil electrode configuration was approximately 14 J. The electrode configuration of this patient was found to have a very low impedance, suggesting a partial short in the current delivery to the heart. The remaining 34 patients in this group had defibrillation threshold energies below 7.5 J. In addition, 100% success with the first test shock could be achieved with energies of only 2.0 times defibrillation threshold with the coil electrodes.

Additional factors may influence defibrillation success. Most patients (50 of 51) in this study had no myopathology. Patients who are candidates for an implanted device often have extensive myocardial pathology and ischemia, which may or may not alter defibrillation threshold. Also, these studies were short term. The effects of long-term lead placement and antiarrhythmic drug therapy on defibrillation remains controversial and requires further investigation.

Since Mirowski and colleagues first described the concept of an implantable defibrillator, there has been a great interest in searching for the optimum electrode configuration and the best method for predicting defibrillation success. From these studies, we conclude that the sequential pulse shock with moderate-sized electrodes provides acceptably low-energy requirements for defibrillation. In addition, a single measurement of defibrillation threshold can be used to predict subsequent defibrillation for an individual patient. The value of approximately 2.6 times defibrillation threshold should approximate 100% successful defibrillation with the first shock for the electrode system. Finally, the determination of population curves of success and defibrillation threshold ratio may be valuable in estimating safety margin for any particular electrode system.

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**References**


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