Automated impedance-based energy adjustment for defibrillation: experimental studies

RICHARD E. KERBER, M.D., DAVID MCPHERSON, M.D., FRANCIS CHARBONNIER, PH.D., ROBERT KIESO, M.S., AND PAMELA HITE, B.S.

ABSTRACT In defibrillation, current flow depends on the energy selected and the transthoracic impedance. If transthoracic impedance is high, current flow may be inadequate to defibrillate. We developed a method by which high transthoracic impedance is automatically compensated for by an increase in operator-selected energy when impedance is high. Transthoracic impedance was predicted in advance of the first shock by passing a low-level current between the defibrillator electrodes during the defibrillator charge cycle; a microprocessor monitored current flow and determined impedance. In 28 mongrel dogs we manipulated transthoracic impedance by placing glycerin-soaked gauze pads between the paddle electrodes and the chest. If the predicted impedance exceeded a preset value, the delivered energy was automatically increased by 40% or 100%. Using this impedance-based energy adjustment technique, we found significant improvements in current flow and success rate of shocks when energy was automatically increased to compensate for high transthoracic impedance. The use of transthoracic impedance as a basis for energy adjustment appears promising technique to minimize the hazards of high electrical energy; it allows low-energy shocks in most patients while avoiding inappropriate low energies in patients with high impedance. Clinical trials are justified.


DEFIBRILLATION is accomplished by passage of sufficient electrical current through the heart to depolarize a critical mass of myocardium. The amount of current that flows therefore becomes critical. Current flow is dependent on two factors: the energy selected by the operator and the transthoracic impedance. Impedance can be reduced to some degree by firm operator pressure on the electrodes, and this will enhance current flow. If pressure is already maximal, the energy selected and the inherent transthoracic impedance then become the major determinants of whether current flow sufficient to defibrillate will be achieved.

High electrical energies can be used for defibrillation in most patients, but have been shown to cause histologic abnormalities in animals and atrioventricular block in humans. Gascho et al. found that when total delivered energy exceeded 240 J, the defibrillation rate fell significantly. Ideally, one should administer the lowest possible energy shock that will minimize damage but still achieve defibrillation.

Unfortunately, the energy and current requirements for defibrillation appear to vary considerably between patients, making it impossible to identify a single energy level that could accomplish both aims in all patients.

At any given energy impedance is the major determinant of current flow. It is therefore predictable that in patients with high transthoracic impedance, a low-energy shock might fail to achieve adequate current flow to defibrillate. We have recently confirmed this in patients in ventricular fibrillation who had a high transthoracic impedance. In these patients 100 J shocks had a success rate of only 22%, as opposed to 68% success when impedance was low or average. Thus, if it were known in advance that a patient had high transthoracic impedance, selection of a low-energy shock would be inappropriate since it would be unlikely to achieve defibrillation; a high-energy shock would be necessary. Conversely, if impedance were low or average, a low-energy shock would be preferable since it would probably be adequate to defibrillate and would be less likely to cause myocardial toxicity.

We now have the ability to accurately predict transthoracic impedance before any shocks are given. This should facilitate appropriate energy selection based on impedance. The hypotheses of this study
were two: (1) The success of a shock of any given energy with regard to defibrillation is related to the transthoracic impedance; shock success falls as impedance rises. (2) High impedance can be automatically compensated for by increasing the shock energy, which will improve the success rate of the defibrillation procedure.

Methods

The study was performed with 28 mongrel dogs weighing 18 to 22 kg. The animals were anesthetized with intravenous pentobarbital; supplemental anesthesia was administered as necessary. The dogs underwent endotracheal intubation and positive pressure ventilation. Arterial pressure was monitored via a polyethylene cannula inserted in a brachial artery. Ventricular fibrillation was induced by passing a train of rectangular impulses (20 V, 9 msec in duration, 60 Hz frequency) for 5 sec down a bipolar electrode catheter that had been inserted in the right jugular vein and passed to the apex of the right ventricle. Ventricular fibrillation was allowed to persist for 15 sec before any shock was given.

All shocks were given from 8 cm diameter electrode ‘‘paddles’’ that were pressed against each dog’s shaved chest by a mechanical holding device that maintained constant electrode-chest contact pressure. One electrode was placed over the palpable cardiac apex on the left chest, the other in a similar location against the right chest. We used two Hewlett-Packard defibrillators, model 78670 A, which delivered damped sinusoidal waveform shocks. These defibrillators estimated transthoracic impedance just before each shock was delivered. The impedance prediction technique we used was originally suggested by Geddes et al. 13 and has been validated by us in humans. 12 Briefly, when the defibrillator charge cycle was initiated a low-level current was passed between the electrodes. The current flow was monitored by a microprocessor and the impedance was estimated by comparison of this current flow with that achieved against known impedances.

One defibrillator was specially modified for this study to automatically alter the operator-selected energy, based on the predicted impedance. In the first part of the study, if the predicted impedance exceeded a high-impedance threshold arbitrarily designated as 70 Ω the defibrillator automatically increased the shock energy one step of the energy dial settings available, i.e., 50 J was automatically increased to 70 J, 100 J to 150 J, and 150 J to 200 J (average 40% increase). In the second part of the study we further modified the defibrillator so that if the predicted impedance exceeded an arbitrary threshold value the shock energy was automatically increased two steps of the energy settings available, i.e., 50 J was automatically increased to 100 J, 100 J to 200 J, and 150 J to 300 J (average 100% increase). As part of this further modification, the threshold impedance value arbitrarily designated as high was altered to 80 Ω.

Transthoracic impedance was increased by placing from one to three gauze pads between the electrodes and the chest. To create a high-impedance medium these gauze pads were soaked with a high-impedance mixture of glycerin and Redux electrode paste, in a ratio of 12:1, before insertion between the chest and the electrodes.

The exact protocol used was as follows: Each dog received shocks for ventricular fibrillation at three selected energy dial settings (50, 100, and 150 J). Each dog received at least four consecutive shocks at each energy setting; the energy settings were used in random order. If a shock of a certain energy failed to defibrillate it was immediately repeated up to four times; then, if necessary, a high-energy shock of 300 or 360 J, which

defibrillated in every case, was administered. Both defibrillators (one of which contained the impedance-based energy adjustment modification) were used at each of the three energy settings. The order in which each defibrillator was used was varied on alternate days. Shocks were given under low transthoracic impedance conditions (i.e., no gauze pads used) and under at least two increased-impedance conditions in each animal (i.e., one to three gauze pads); we thereby obtained a range of impedances from 30 to 160 Ω. After each shock the energy selected, energy actually delivered, current flow, and actual impedance to the delivered shock were annotated on the electrocardiographic hard copy writeout of the defibrillator. Subsequently we used these data to construct curves of the success rate of each shock with regard to defibrillation (% success) vs impedance for each defibrillator type (standard and modified) for each of the two parts of the study. These data were subsequently plotted in impedance increments of 20 Ω.

Statistical analysis was done with use of the SAS software system run on an IBM 370 computer. A general linear model procedure was used to obtain least squares fit of an analysis of variance model with the Bonferroni adjustment. Three treatment factors were incorporated in a saturated design involving all possible treatment interactions. The treatment factors were the selected energy level (50, 100, or 150 J), the use of the standard or modified defibrillator, and the transthoracic impedance. For each hypothesis tested, the null hypothesis was rejected if the p value was less than .05. In addition, Student’s t test was used to compare the success rates of shocks from modified vs standard defibrillators at each energy (50, 100, 150 J) for the grouped subthreshold and suprathreshold impedances for each of the two parts of the study.

Results

The data on selected energy, actual delivered energy, current, and % success for each of the three energy settings are presented in tables 1 and 2. In these tables we have classified the data by the impedance categories of less than 70 Ω (part 1) or less than 80 Ω (part 2), below which threshold impedances the energy-increasing modification was inoperative and the modified defibrillator functioned as a standard defibrillator, and greater than 70 or 80 Ω, at which levels the modification was operative and the energy level was automatically increased by one or two steps. Tables 1 and 2 show that for each energy setting (50, 100, and 150 J), when impedances were less than 70 or 80 Ω there were no significant differences in delivered energy, current, or % success between the modified and standard defibrillators, as expected. However, when the impedance was greater than 70 or 80 Ω, the impedance-based automatic energy increase resulted in significantly higher levels of delivered energy, current, and % success at each of the three selected energy levels (50, 100, 150 J).

A more detailed presentation of the effects of increasing impedance on % success is given in figures 1 and 2. In these figures, to focus on the effects of impedance, we have grouped the impedance data into 20 Ω increments and by type of defibrillator (modified vs
TABLE 1
Energy, current, and % success in part 1 of study

<table>
<thead>
<tr>
<th>Selected energy (J)</th>
<th>Defibrillator</th>
<th>Delivered energy (J)</th>
<th>Current (A)</th>
<th>% success</th>
<th>Delivered energy (J)</th>
<th>Current (A)</th>
<th>% success</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Standard</td>
<td>51.3 ± 0.5</td>
<td>21.0 ± 0.6</td>
<td>52.5 ± 9.7</td>
<td>55.8 ± 0.2</td>
<td>14.0 ± 0.3</td>
<td>19.3 ± 4.7</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td>51.5 ± 0.7</td>
<td>21.6 ± 0.5</td>
<td>74.4 ± 9.1</td>
<td>77.4 ± 0.6</td>
<td>16.6 ± 0.4</td>
<td>38.7 ± 6.6</td>
</tr>
<tr>
<td>100</td>
<td>Standard</td>
<td>102.4 ± 0.7</td>
<td>29.7 ± 0.7</td>
<td>82.6 ± 6.4</td>
<td>111.2 ± 0.3</td>
<td>20.1 ± 0.4</td>
<td>49.5 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td>101.8 ± 0.8</td>
<td>30.4 ± 0.7</td>
<td>93.2 ± 3.8</td>
<td>165.4 ± 0.5</td>
<td>24.4 ± 0.5</td>
<td>78.2 ± 5.6</td>
</tr>
<tr>
<td>150</td>
<td>Standard</td>
<td>152.0 ± 1.2</td>
<td>36.4 ± 0.9</td>
<td>90.7 ± 5.3</td>
<td>164.0 ± 0.4</td>
<td>24.8 ± 0.4</td>
<td>69.0 ± 6.0</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td>151.4 ± 2.0</td>
<td>38.1 ± 0.8</td>
<td>94.8 ± 3.6</td>
<td>219.7 ± 1.7</td>
<td>28.1 ± 0.5</td>
<td>74.5 ± 5.4</td>
</tr>
</tbody>
</table>

Values are mean ± SEM.
Energy automatically increased when impedance was greater than 70 Ω.

*p < .05, modified vs standard; ^p < .01, modified vs standard.

standard), while the data from the three selected energy classifications have been averaged. The number of observations averaged for each point on the graph ranges from 12 to 20. In both figures, the decline in % success with increasing impedance is significant (p < .05). When the modified and standard defibrillators were compared, the differences between the % success of shocks above the arbitrary threshold values of 70 and 80 Ω achieve significance between impedances of 71 to 130 Ω in part 1 and 101 to 140 Ω in part 2.

Discussion

The main points we have made are as follows: (1) At any given selected energy, the success rate of shocks given to defibrillate falls as transthoracic impedance rises; high transthoracic impedance is associated with a low shock success rate, especially when selected energy is low. (2) It is possible to automatically increase energy to compensate for high transthoracic impedance, and a significant improvement in current flow and shock success rate results.

Because attempts at defibrillation with electrical energy and current can cause histologic and functional myocardial toxicity, recommendations for initial energy selection in defibrillation have been lowered in recent years. At present the American Heart Association recommends use of initial shocks of as low as 200 J,18 and there is convincing clinical experience available to support this position.5-6 Several reports of the results of shocks of 100 J or less are also available. Campbell et al.,13 using delivered energies of 74 to 82 J, defibrillated 53 of 94 patients (56%). Gascho et al.4 defibrillated seven of nine patients (78%) with shocks of 80 J delivered energy. On the other hand, Patton and Pantridge11 reported that only nine of 24 patients (38%) were defibrillated by stored energy of 100 J. One explanation for these divergent results might be that these earlier reports did not consider the effect of transthoracic impedance on shock success. We recently showed that when patients receiving 100 J shocks were classified into high transthoracic impedance and average transthoracic impedance groups, the first-shock

TABLE 2
Energy, current, and % success in part 2 of study

<table>
<thead>
<tr>
<th>Selected energy (J)</th>
<th>Defibrillator</th>
<th>Delivered energy (J)</th>
<th>Current (A)</th>
<th>% success</th>
<th>Delivered energy (J)</th>
<th>Current (A)</th>
<th>% success</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Standard</td>
<td>50.1 ± 0.6</td>
<td>22.6 ± 0.7</td>
<td>59.2 ± 11.6</td>
<td>55.9 ± 0.3</td>
<td>13.7 ± 0.4</td>
<td>15.8 ± 6.4</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td>49.8 ± 0.7</td>
<td>22.8 ± 0.8</td>
<td>64.5 ± 11.3</td>
<td>111.3 ± 0.6</td>
<td>20.1 ± 0.8</td>
<td>36.7 ± 9.8</td>
</tr>
<tr>
<td>100</td>
<td>Standard</td>
<td>99.8 ± 1.2</td>
<td>32.1 ± 1.0</td>
<td>82.3 ± 6.7</td>
<td>110.9 ± 0.5</td>
<td>20.4 ± 0.6</td>
<td>41.7 ± 8.7</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td>99.4 ± 1.5</td>
<td>32.5 ± 1.2</td>
<td>88.5 ± 8.2</td>
<td>221.8 ± 1.2</td>
<td>28.9 ± 1.0</td>
<td>73.5 ± 8.2</td>
</tr>
<tr>
<td>150</td>
<td>Standard</td>
<td>147.0 ± 1.8</td>
<td>40.2 ± 1.2</td>
<td>100 ± 0</td>
<td>164.4 ± 0.7</td>
<td>24.9 ± 0.8</td>
<td>68.0 ± 8.5</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td>147.6 ± 2.0</td>
<td>39.7 ± 1.3</td>
<td>94.5 ± 5.5</td>
<td>334.0 ± 1.8</td>
<td>36.1 ± 1.3</td>
<td>92.5 ± 4.3</td>
</tr>
</tbody>
</table>

Values are mean ± SEM.
Energy automatically increased when impedance was greater than 80 Ω.

*p < .05, modified vs standard; ^p < .01, modified vs standard.
success rate was markedly different depending on the impedance; success varied from 20% to 68%. This suggests that if selection of first-shock energy could be based on anticipated impedance, in most patients with average transthoracic impedance a shock of 100 J could be used effectively, reducing the hazard of myocardial toxicity from high energy, while the high-impedance patients could receive the higher energies they require. However, to make this clinically feasible, a method had to be developed by which transthoracic impedance could be accurately predicted in advance of any attempt at defibrillation. Such a method has now been developed and tested by us in humans and was used in this study to provide the information on which the automated energy adjustment was based.

Geddes et al. showed that the weight-based current requirements for defibrillation of animals were relatively constant over a wide range of sizes and species. If this were true for humans also, it would be relatively simple, knowing impedance in advance, to automatically select an energy level sufficient to generate a threshold current. Unfortunately, several studies have shown that the range of energy and current requirements for human defibrillation is quite wide; generation of a current sufficient for defibrillation in almost all patients would result in the administration of excessive energy and current to most, and would defeat the purpose of this approach. Instead, we chose to automatically increase the energy by arbitrary amounts when the impedance exceeded a threshold level that approximated the mean transthoracic impedance observed in humans. This resulted in current increases of 15% and 42%, respectively, in the two parts of the study, with a corresponding improvement in success rate. Although tripling the energy level would undoubtedly result in further current increases and improvement in success rate, each further increase in energy would increase the likelihood of myocardial toxicity.

This approach should be beneficial to patients by encouraging use of low-energy shocks when appropriate while avoiding use of low energies in high-impedance patients who require higher energy shocks. Two important questions need to be answered in humans. (1) Should automated increases in energy begin at the threshold impedance levels we arbitrarily selected in this study (70 to 80 Ω, the mean transthoracic impedance in patients), or will there be demonstrable benefit only at much higher impedance levels? (2) Is a doubling of selected energy sufficient in high-impedance patients, or should the energy level be adjusted even higher? Clinical trials using an approach similar to that in this study will be necessary to answer these questions.

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