Advance prediction of transthoracic impedance in human defibrillation and cardioversion: importance of impedance in determining the success of low-energy shocks

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ABSTRACT The purposes of this study were to evaluate a method that predicts transthoracic impedance in advance of defibrillating shocks in humans and to assess the importance of transthoracic impedance in low-energy defibrillation. Via defibrillator electrodes we applied 31 kHz current to the chest during the defibrillator charge cycle, before the defibrillating shock was actually delivered. The current flow was limited by transthoracic impedance; a microprocessor monitored the predischarge current flow and determined the predischarge impedance by calibration against known resistance values. Actual impedance to the defibrillating shock was also determined and compared with the predicted impedance. With this approach we predicted impedance in 19 patients who received 66 shocks for ventricular and atrial arrhythmias. Predicted impedance (y) correlated very well with actual impedance (x): y = .90x + 11.3; r = .97. To determine the importance of impedance in defibrillation and cardioversion, we prospectively gathered data from 96 patients who received shocks of various energies for ventricular or atrial arrhythmias. In patients with high transthoracic impedance (> 97 Ω), low-energy shocks (≤ 100 J) for ventricular defibrillation had only a 20% success rate as opposed to a 70% success rate for low-energy shocks in patients with low or average impedance (p < .05). We conclude that transthoracic impedance can be accurately predicted in advance of defibrillation and cardioversion. This method permits the preshock identification of patients with high impedance in whom attempts to defibrillate with low-energy shocks are inappropriate.


ATRIAL and ventricular arrhythmias can be terminated by a damped sinusoidal electrical shock. The operator selects the shock energy (joules), but defibrillation or cardioversion is achieved by passage of current (amperes) through the heart; the current depolarizes ventricular or atrial myocardium.1–5 The current flow must be adequate to depolarize a critical mass of myocardium to achieve defibrillation.1, 2 If the current flow is inadequate to depolarize such a critical mass, defibrillation will occur infrequently or not at all.1, 2, 6

Current flow has two principal determinants that potentially can be altered by the operator of a damped sine-wave defibrillator: the energy selected and the transthoracic impedance. If transthoracic impedance is high, more energy will be required to achieve an adequate current for defibrillation. The American Heart Association at present suggests that initial shocks to terminate ventricular fibrillation should be 200 J or more.7 However, shocks of energies of 100 J or even less have been reported to be effective in the majority of patients who received them6, 9 and may cause less severe cardiac toxicity than higher energies.9–12 This may encourage clinicians to choose low energies for initial attempts to defibrillate.

The combination of low selected energy plus high transthoracic impedance may result in low current flow that is inadequate to achieve defibrillation. If an initial low-energy shock fails to defibrillate, the usual clinical practice is to repeat shocks at progressively higher energies until successful, but the combination of multiple shocks and a longer duration of ventricular fibrillation and ischemia increases the chances of myocardial
damage.\textsuperscript{13, 14} If transthoracic impedance could be accurately determined in advance of defibrillation or cardioversion, inappropriately low energies could be avoided in patients with known high transthoracic impedance. This would help reduce the number of shocks required and avoid unnecessary delays in restoring sinus rhythm.

Transthoracic impedance can be determined by commercially available defibrillators,\textsuperscript{15} and methods for predicting transthoracic impedance by applying high-frequency current to the chest in advance of attempts to defibrillate have been described in experimental animals.\textsuperscript{16, 17} It has not yet been determined whether such methods can accurately predict human transthoracic impedance in advance. The first purpose of our study was to evaluate the ability of low-level, high-frequency electrical current given in advance of defibrillating shocks to predict transthoracic impedance in patients undergoing emergency defibrillation and elective cardioversion. The second purpose was to determine the relationship of high transthoracic impedance to the success of low-energy shocks given for ventricular and atrial arrhythmias. We hypothesized that when transthoracic impedance is high, low-energy shocks often will fail to defibrillate because they generate inadequate current flow; in such patients higher energy shocks will be necessary to generate the minimum current flow necessary to defibrillate.

Methods

The study was approved by the University of Iowa Human Research Committee. Data were collected prospectively from a total of 96 patients receiving shocks for ventricular fibrillation ("defibrillation") and for ventricular tachycardia, atrial fibrillation, or atrial flutter ("cardioversion"). We defined defibrillation as the conversion of ventricular fibrillation to an organized rhythm, usually sinus rhythm. We defined cardioversion as the conversion of ventricular tachycardia to a supraventricular rhythm or the conversion of atrial fibrillation or atrial flutter to sinus rhythm.

The patients underwent defibrillation or cardioversion in the coronary care unit, emergency room, electrophysiology laboratory, or inpatient wards. For the initial portion of this study (impedance prediction) the electrodes used were either standard hand-held electrode paddles or self-adhesive electrode pads; the two types of electrodes are equally effective.\textsuperscript{18} In the second phase of the study (relationship of shock success to transthoracic impedance) we analyzed data from an ongoing, prospective study of self-adhesive, monitor-defibrillator pads for defibrillation and cardioversion.\textsuperscript{18} All the latter patients received shocks from self-adhesive electrode pads; thus the shock technique used was homogeneous.

The following protocols for energy selection were used in both phases of the study: For defibrillation we recommended that the operator select an initial shock energy setting of 100 J (energy that would be delivered to a 50 $\Omega$ resistance). If the initial 100 J shock failed to defibrillate, we recommended stepwise increases: 200, 300, and finally 360 J (Hewlett-Packard defibrillator) or 400 J (Datascope defibrillator). To perform cardioversion of ventricular tachycardia, initial shocks of 100 J were also recommended, with stepwise increases as above. For the cardioversion of atrial fibrillation we recommended initial shocks of 100 J with stepwise increases as above. For atrial flutter we recommended an initial shock of 20 J, with subsequent increases to 40 J, 100 J, etc. The physicians supervising the procedures were allowed to choose lower or higher initial shock energies at their discretion. In no case, however, were the physicians aware of the predicted impedance when choosing the initial shock energy, nor were they allowed to see the actual impedance value after the first shock was given. This was done to avoid altering or biasing energy selection for the initial or subsequent shocks.

Shocks were given from either Datascope MD2J defibrillators or Hewlett Packard defibrillators (models 78660A and 78660B). The Hewlett Packard defibrillators were modified to allow advance prediction of transthoracic impedance. The measurement circuit (figure 1) used a high-frequency signal passed through the patient via the paddles. This signal flowed only during the defibrillator charge cycle and caused no delay in the defibrillation or cardioversion procedures. Transthoracic impedance limited the current flow, which was monitored by a microprocessor within the defibrillator. The impedance so measured depends on signal frequency and amplitude. In this study, a signal frequency of 31 kHz was chosen for three reasons: (1) that specific frequency was available from a crystal-controlled source already present in the instrument, (2) it was in the range shown by Geddes et al.\textsuperscript{16} to provide reasonably accurate prediction of discharge impedance in animal studies, and (3) it was sufficiently high to minimize patient sensitivity, so that a reliable measurement could be made at a radiofrequency signal level considerably below the safe limit specified by electrical safety standards for cardiac and respiratory monitoring equipment. The circuit was calibrated against known resistance values and the predicted (predischARGE) impedance entered into a microprocessor table for printout on the annotating recorder. When the defibrillator was actually discharged, the current flow through the patient and the patient impedance during the discharge were also monitored by the microprocessor and printed out on the recorder,\textsuperscript{13} allowing comparison of the two measurements, the predicted (predischARGE) impedance and the actual impedance to the defibrillating shock.

To determine the relationship of predicted to actual transthoracic impedance, we derived linear regression equations, using the least-squares method, to compare the two impedances in six different ways: (1) predicted vs actual impedances to all individual shocks from all patients, (2) predicted vs actual impedance to only the first shock given at each different selected energy level in each patient, (3) average predicted vs average actual impedance from each patient (i.e., in each patient we averaged the impedances to all shocks that patient received, then plotted one average predicted and actual impedance value from that patient), (4) predicted vs actual impedances to shocks given at three different selected energy ranges (< 100, 100 to 200, and > 200 J), (5) predicted vs actual impedances to all individual shocks from defibrillators equipped with hand-held paddle electrodes, and (6) predicted vs observed impedances to all individual shocks from defibrillators equipped with self-adhesive electrode pads.

The actual impedance to all individual shocks in the 19 patients in the impedance prediction phase of the study was 78 ± 19 $\Omega$ (see Results and table 1). On the basis of this, we classified the patients into two groups: those patients whose actual impedance exceeded 1 SD above the mean (i.e., > 97 $\Omega$) were considered to have high impedance, while all others were considered to have low or average impedance. We then used a chi-square
test to compare the two groups with regard to the success of shocks of different energies for defibrillation or cardioversion for each arrhythmia. In addition, we compared the minimum current, current per kilogram of body weight, and delivered energy that achieved defibrillation in the two groups by using an unpaired t test.

Results

Advance prediction of transthoracic impedance (19 patients). Impedance prediction data were obtained from 19 patients who received a total of 66 shocks from the specially modified defibrillators. The arrhythmias for which the initial shocks were given were ventricular fibrillation (three patients), ventricular tachycardia (three patients), atrial fibrillation (eight patients), atrial flutter (four patients), and supraventricular tachycardia (one patient). No patient recalled any discomfort during the defibrillator charge cycle while the 31 kHz current was flowing across the chest. The average impedance of each patient was calculated for the initial shocks given at different selected energy ranges: <100 J (75.4 ± 21.2 Ω), 100–200 J (76.0 ± 14.3 Ω), and >200 J (81.8 ± 10.7 Ω). The impedance to shocks given from hand-held paddle electrodes (79.0 ± 15.0 Ω) was significantly higher than that given from self-adhesive pad electrodes (77.1 ± 23.1 Ω). The correlation between actual and predicted impedances was calculated using the formulas:

\[ y = \beta_0 + \beta_1 x + \epsilon \]

where \( y \) is the predicted impedance, \( x \) is the actual impedance, and \( \epsilon \) is the error term. The regression coefficients were calculated using the least squares method, and the correlation coefficient \( r \) was calculated using the following formula:

\[ r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}} \]

The correlation coefficients for the different energy ranges were as follows:

- <100 J: \( r = .89 \) (p < .001)
- 100–200 J: \( r = .88 \) (p < .001)
- >200 J: \( r = .94 \) (p < .001)

The correlation coefficients for the different electrode types were as follows:

- Hand-held paddle electrodes: \( r = .91 \) (p < .001)
- Self-adhesive pad electrodes: \( r = .90 \) (p < .001)

The results are summarized in Table 1.

**TABLE 1**

Impedance prediction: comparison of actual vs predicted impedance (Ω) in 19 patients

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Actual impedance (mean ± SD)</th>
<th>Predicted impedance (mean ± SD)</th>
<th>n</th>
<th>Regression equation</th>
<th>r value</th>
</tr>
</thead>
<tbody>
<tr>
<td>From all patients</td>
<td>78.1 ± 19.4</td>
<td>81.4 ± 17.9</td>
<td>66</td>
<td>( y = .90x + 11.3 )</td>
<td>.97</td>
</tr>
<tr>
<td>First shock impedance at each selected energy level in each patient</td>
<td>75.4 ± 22.1</td>
<td>79.8 ± 20.8</td>
<td>45</td>
<td>( y = .92x + 10.5 )</td>
<td>.98</td>
</tr>
<tr>
<td>Average impedance of each patient</td>
<td>71.2 ± 21.9</td>
<td>75.4 ± 21.2</td>
<td>19</td>
<td>( y = .95x + 7.6 )</td>
<td>.99</td>
</tr>
<tr>
<td>Impedance to shocks given at different selected energy ranges:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;100 J</td>
<td>74.5 ± 32.0</td>
<td>76.1 ± 28.9</td>
<td>17</td>
<td>( y = .89x + 9.8 )</td>
<td>.99</td>
</tr>
<tr>
<td>100–200 J</td>
<td>76.0 ± 14.3</td>
<td>81.5 ± 13.1</td>
<td>25</td>
<td>( y = .88x + 14.0 )</td>
<td>.96</td>
</tr>
<tr>
<td>&gt;200 J</td>
<td>81.8 ± 10.7</td>
<td>85.0 ± 10.7</td>
<td>24</td>
<td>( y = .94x + 8.0 )</td>
<td>.94</td>
</tr>
<tr>
<td>Impedance to shocks given from hand-held paddle electrodes</td>
<td>79.0 ± 15.0</td>
<td>81.4 ± 14.1</td>
<td>33</td>
<td>( y = .91x + 9.9 )</td>
<td>.97</td>
</tr>
<tr>
<td>Impedance to shocks given from self-adhesive pad electrodes</td>
<td>77.1 ± 23.1</td>
<td>81.3 ± 21.3</td>
<td>33</td>
<td>( y = .90x + 12.1 )</td>
<td>.98</td>
</tr>
</tbody>
</table>

\( \beta_0 = \text{predicted impedance}; \beta_1 = \text{actual impedance}. \)
in this phase of the study (table 1). Four of the initial 19 patients had first-shock actual impedances of 99 to 118 Ω (more than 1 SD above the mean). In each of these patients, a high first-shock impedance was correctly predicted in advance, with errors ranging from 0 Ω (99 Ω patient) to 9 Ω (118 Ω patient; 8% error).

**Relationship of success to transthoracic impedance** (96 **patients**). We identified a total of 96 patients who received shocks from self-adhesive pads for defibrillation or cardioversion; shocks were given for 116 arrhythmias in these patients (i.e., some patients had more than one type of arrhythmia). These data are summarized in table 2. Seventeen of the 96 patients had high transthoracic impedances. In patients with ventricular fibrillation, only two of 10 (20%) low-energy shocks achieved defibrillation in high-impedance patients, whereas 21 of 30 (70%) low-energy shocks succeeded when transthoracic impedance was in the low or average range (p < .05). For ventricular tachycardia, only one of three low-energy shocks was successful in patients with high impedance, while 62 of 70 low-energy shocks succeeded when impedance was average (p < .1 > .05). For atrial fibrillation, none of four low energy shocks was successful in patients with high impedance, whereas 27 of 41 (66%) such shocks were successful in patients with low to average impedance (p < .05).

Twenty-five patients received shocks for ventricular fibrillation. In 19 of these 25 patients at least one shock of 100 J or less was given. In this subgroup receiving low-energy shocks for ventricular fibrillation we assessed the lowest current that actually achieved defibrillation in each patient (note that this is not a true minimum current determination, since some patients might have required less than 100 J energy for defibril-
TABLE 3
Energy and current requirements for ventricular defibrillation in 19 patients receiving at least one shock \( \leq 100 \) J

<table>
<thead>
<tr>
<th>Lowest current that achieved defibrillation (A)</th>
<th>Patients with average impedance (&lt;97 Ω)</th>
<th>Patients with high impedance (&gt;97 Ω)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(range 23–44)</td>
<td>28.7 ± 6.2</td>
<td>27.6 ± 8.1</td>
<td>NS</td>
</tr>
<tr>
<td>Lowest current/body weight that achieved defibrillation (A/kg)</td>
<td>0.35 ± 0.10</td>
<td>0.32 ± 0.13</td>
<td>NS</td>
</tr>
<tr>
<td>(range 0.22–0.63)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lowest delivered energy that achieved defibrillation (J)</td>
<td>134.6 ± 46.4</td>
<td>211.0 ± 109.3</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>(range 103–217)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion

There are two major points evident from this study. First, we have shown that it is possible to accurately predict transthoracic impedance in advance of actual defibrillating shocks. Second, we have shown that transthoracic impedance is a major determinant of the energy requirements for defibrillation and cardioversion. Specifically, we found that shocks of \( \leq 100 \) J have an unsatisfactory rate of defibrillation or cardioversion in patients with high transthoracic impedance. Such low-energy shocks should not be selected for patients with high impedance.

Previous investigators have noted considerable interpatient variation in the energy requirements for transthoracic defibrillation.\(^8\)-\(^{12}\)\(^\text{19}\) This investigation similarly found a wide range of energies were required; beginning at 100 J and progressively increasing the energy as necessary, we found that defibrillation was accomplished in some patients at the initial energy level but required up to 394 J in others. Factors that influence the energy requirements and success of shocks given for defibrillation or cardioversion include the duration of arrhythmias preceding the shock, metabolic abnormalities, the state of the myocardium, and several others.\(^10\)-\(^{19}\) In this study, our hypothesis was that transthoracic impedance is a major determinant of the energy requirements for defibrillation and cardioversion. Specifically we hypothesized that when impedance is high, relatively high shock energies will be required to generate adequate current to achieve defibrillation or cardioversion; low-energy shocks would be likely to fail when impedance is high. This is, in fact, what we found. For example, in patients with ventricular fibrillation who had high transthoracic impedance (\( > 97 \) Ω), only 20\% of low-energy shocks achieved defibrillation as opposed to the 70\% success rate of such low-energy shocks in patients who had average transthoracic impedance (figure 3). Note that the lowest current that achieved defibrillation was the same in the average-impedance vs high-impedance groups, but the patients with high impedance required substantially greater energy to generate that current (table 3).

Since transthoracic impedance is a major determinant of defibrillation and cardioversion energy requirements, knowing impedance in advance should allow
selection of a first-shock energy level appropriate for the patient’s impedance. We have shown that it is possible to accurately predict impedance in advance. Prediction of high impedance should alert the operator to avoid inappropriately low-energy shocks, which are likely to fail because they will generate inadequate current. Conversely, prediction of low or average impedance should suggest the use of initial shocks of ≤ 100 J for defibrillation or cardioversion; such energies have a good success rate when impedance is low and avoid excessive current, which could cause myocardial damage.\textsuperscript{13, 14}

We found a wide degree of variability in the minimum current required for defibrillation in humans; this is in agreement with results of earlier studies by Patton and Pantridge\textsuperscript{5} and by us.\textsuperscript{6} Note that this is different from findings in animals. Geddes et al.\textsuperscript{20} found that a current of 1 A/kg was adequate to achieve defibrillation in animals of widely different size, and there was relatively little variation in this requirement. The reasons for the differences in current requirement between experimental animals and humans probably include various durations of preshock ventricular fibrillation (usually induced for only brief periods of time in animals but often prolonged in patients), associated metabolic abnormalities, and the presence and severity of the underlying heart disease (usually none in animals but often severe in patients).

We found a large range of transthoracic impedances, from 28 to 118 Ω. This has also been reported previously.\textsuperscript{21, 22} The distance between the paddle electrodes is a major determinant of transthoracic impedance,\textsuperscript{22} and this is primarily a function of chest size. Increasing pressure on hand-held electrode paddles has been shown to lower impedance in experimental animals,\textsuperscript{22} probably by improving electrode-chest contact. Thus advance prediction of high impedance should alert the operator to increase pressure if hand-held paddle electrodes are being used. This will reduce impedance and increase current flow at any energy. However, this maneuver would not be possible if self-adhesive electrode pads were being used.

In summary, this study demonstrates that rapid and accurate prediction of transthoracic impedance in advance of a defibrillating shock is feasible and safe. Advance knowledge of high transthoracic impedance can alert the operator to avoid inappropriately low energies for initial attempts at defibrillation and cardioversion and/or to increase pressure on hand-held paddle electrodes. Either or both maneuvers will increase current flow and should improve the chances of first-shock defibrillation and cardioversion.

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Circulation. 1984;70:303-308
doi: 10.1161/01.CIR.70.2.303
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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