Transthoracic Cardioversion of Atrial Fibrillation
Comparison of Rectilinear Biphasic Versus Damped Sine Wave Monophasic Shocks

Suneet Mittal, MD; Shervin Ayati, MSEE; Kenneth M. Stein, MD; David Schwartzman, MD; Doris Cavlovich, RN, BSN; Patrick J. Tchou, MD; Steven M. Markowitz, MD; David J. Slotwiner, MD; Marc A. Scheiner, MD; Bruce B. Lerman, MD

Background—Clinical studies have shown that biphasic shocks are more effective than monophasic shocks for ventricular defibrillation. The purpose of this study was to compare the efficacy of a rectilinear biphasic waveform with a standard damped sine wave monophasic waveform for the transthoracic cardioversion of atrial fibrillation.

Methods and Results—In this prospective, randomized, multicenter trial, patients undergoing transthoracic cardioversion of atrial fibrillation were randomized to receive either damped sine wave monophasic or rectilinear biphasic shocks. Patients randomized to the monophasic protocol (n=77) received sequential shocks of 100, 200, 300, and 360 J. Patients randomized to the biphasic protocol (n=88) received sequential shocks of 70, 120, 150, and 170 J. First-shock efficacy with the 70-J biphasic waveform (60 of 88 patients, 68%) was significantly greater than that with the 100-J monophasic waveform (16 of 77 patients, 21%, P<0.0001), and it was achieved with 50% less delivered current (11±1 versus 22±4 A, P<0.0001). Similarly, the cumulative efficacy with the biphasic waveform (83 of 88 patients, 94%) was significantly greater than that with the monophasic waveform (61 of 77 patients, 79%; P=0.005). The following 3 variables were independently associated with successful cardioversion: use of a biphasic waveform (relative risk, 4.2; 95% confidence intervals, 1.3 to 13.9; P=0.02), transthoracic impedance (relative risk, 0.64 per 10-Ω increase in impedance; 95% confidence intervals, 0.46 to 0.90; P=0.005), and duration of atrial fibrillation (relative risk, 0.97 per 30 days of atrial fibrillation; 95% confidence intervals, 0.96 to 0.99; P=0.02).

Conclusions—For transthoracic cardioversion of atrial fibrillation, rectilinear biphasic shocks have greater efficacy (and require less energy) than damped sine wave monophasic shocks. (Circulation. 2000;101:1282-1287.)

Key Words: cardioversion • atrial fibrillation • shock

Atrial fibrillation is the most commonly encountered sustained clinical arrhythmia.1 Since its introduction 3 decades ago, transthoracic electrical cardioversion has remained the most effective method for terminating atrial fibrillation.2 However, currently available defibrillators use a damped sine wave monophasic waveform, which may be effective in <80% of patients.3–6

Multiple studies have shown that biphasic waveforms have greater efficacy than monophasic waveforms for endocardial defibrillation.7–12 More recent studies of transthoracic ventricular defibrillation have also shown that, compared with monophasic shocks, biphasic shocks are equally effective and use less delivered energy,13,14 which may result in less post-shock myocardial dysfunction.13,15–17 To determine whether a biphasic waveform provides increased efficacy with less energy during the transthoracic cardioversion of atrial fibrillation, we prospectively compared the efficacy of a standard damped sine wave monophasic waveform with a rectilinear biphasic waveform in patients undergoing transthoracic cardioversion of atrial fibrillation.

Methods

Study Population

This study was a prospective, randomized, multicenter trial that compared the efficacy of a rectilinear biphasic waveform with a damped sine wave monophasic waveform for the transthoracic cardioversion of atrial fibrillation. During the study period (between August 1998 and February 1999), 174 patients were enrolled from 7 centers. Patients were eligible for the study if they were undergoing electrical cardioversion of atrial fibrillation. Patients with atrial fibrillation for ≥48 hours were anticoagulated with warfarin for ≥3 weeks and achieved an international normalized ratio ≥2.0. Patients who had not been anticoagulated for ≥3 weeks underwent a
transesophageal echocardiogram while receiving therapeutic heparin (or warfarin) immediately before the cardioversion that documented the absence of a left atrial thrombus. All patients were then required to be anticoagulated for 3 to 4 weeks after cardioversion. In addition, all patients were required to have had an echocardiogram within 3 months of the cardioversion for assessment of the left atrial size and left ventricular (LV) ejection fraction. Patients were ineligible if they were <18 years of age, were pregnant, or were undergoing cardioversion of an atrial arrhythmia other than atrial fibrillation. The Institutional Review Board at each participating institution approved the investigational protocol, and informed written consent was obtained from all patients.

**Study Design**

The primary hypothesis of the study was that rectilinear biphasic shocks would have a greater cardioversion efficacy than monophasic shocks. Assuming an 80% cumulative efficacy with the damped sine waveform shock delivered across 50-Ω load, 154 patients were required to detect a >15% difference in efficacy between the monophasic and biphasic waveforms and to have a power of 80% and a significance level of 0.05.

**Shock Waveforms**

Figure 1 depicts a representative 100-J damped sine wave monophasic waveform and a 70-J rectilinear (constant-current first phase) biphasic waveform delivered across a 50-Ω load. The monophasic waveforms were generated by a Zoll PD-2000 defibrillator, which delivered the stored charge on a 45-μF capacitor through a 20-MHz inductor and an internal resistance of 14 Ω. Biphasic waveforms were generated from a 100-μF capacitor using the Zoll PD-2100 defibrillator. The rectilinear biphasic waveform consisted of a constant-current 6-ms first phase, followed by a truncated, exponential 4-ms second phase. The time between the trailing edge of the first phase and the leading edge of the second phase was 100 μs. For a selected energy, a constant-current first phase was produced by automatically adjusting the internal resistance of the defibrillator circuit on the basis of the patient’s transthoracic impedance, which was automatically determined at the onset of shock delivery.

The defibrillator’s internal switching resistors, along with impedance compensation, provided a constant first-phase current as well as the step ripple. The amplitude of the first and second phases varied with the selected energy. The initial amplitude of the second phase was approximately equal to the final amplitude of the first phase. When 170 J was selected for the biphasic waveform and the measured patient impedance was ≥85 Ω, the first phase of the biphasic waveform tilted. However, all other waveform parameters, including phase duration, interphase delay, and integrated impedance measurement-sensing pulse, were unchanged. The effect of transthoracic impedance on delivered current for the monophasic and biphasic waveforms is outlined in Table 1.

**Shock Electrodes**

Wet polymer gel pads (Zoll Cardiology Specialty Pad) for transthoracic cardioversion were applied to the right parasternal area and to the left scapula posteriorly. The anterior electrode was circular and had a diameter of 10 cm, which corresponded to an active surface area of 78 cm². The posterior electrode was rectangular and had a diagonal length of 14.5 cm, which corresponded to an active surface area of 113 cm². The pads were connected to a multiple-defibrillation interface unit, which in turn was connected to the monophasic and biphasic defibrillators. This setup was used to ensure that both defibrillators delivered a shock into the same pad and same location. Furthermore, the interface unit transferred the voltage and current delivered to the patient to a laptop personal computer for data collection purposes.

**Protocol for Cardioversion**

Patients were randomized at each center, using a simple block-randomization scheme, to either the monophasic or biphasic waveform protocol. Patients randomized to the monophasic protocol received sequential shocks of 100, 200, 300, and 360 J, if necessary. If the 360-J shock failed to cardiovert the patient, a final 170 J biphasic shock was delivered. Patients randomized to the biphasic protocol received sequential shocks of 70, 120, 150, and 170 J, if necessary. If the 170-J shock failed to cardiovert the patient, a final 360-J monophasic shock was delivered. Successful cardioversion was defined as the conversion of atrial fibrillation to sinus rhythm for ≥30 s after the shock.

**Statistical Analysis**

All continuous variables are expressed as mean±SD. Comparisons of dichotomous and continuous variables between the monophasic and biphasic waveform groups were calculated using the χ² and Student’s t tests, respectively. The first-shock efficacy of the 70-J biphasic and 100-J monophasic shocks and the cumulative efficacy of biphasic and monophasic shocks were compared using Fisher’s
exact test. To determine the variables independently associated with successful cardioversion, multivariate forward stepwise logistic regression was performed using the following clinical variables: patient weight, duration of atrial fibrillation, left atrial size, LV ejection fraction, transthoracic impedance, and shock waveform used. We calculated 95% confidence intervals for each relative risk. For all comparisons, \( P<0.05 \) was considered statistically significant.

Results

Patient Characteristics

Cardioversion was performed in 174 patients. Nine patients were excluded from analysis. Reasons for exclusion included (1) failure of the investigator to follow the prespecified step-up shock protocol (\( n=7 \)), (2) pretreatment with ibutilide (\( n=1 \)), and (3) inability to access cardioversion shock data due to a computer malfunction (\( n=1 \)). The remaining 165 patients constituted the study population.

The population was 66\( \pm \)12 years of age (range, 30 to 92 years), had a mean weight of 91\( \pm \)23 kg (range, 46 to 168 kg), and was predominantly male (70%). The size of the left atrium was 4.7\( \pm \)0.9 cm (range, 2.7 to 9.7 cm), and the LV ejection fraction was 50\%\( \pm \)14\% (range, 15\% to 75\%). Structural heart disease (including hypertension) was present in 69\% of patients. Of the 165 patients who underwent cardioversion, 88 (53\%) were randomized to the biphasic group and 77 (47\%) to the monophasic group. The 2 groups were similar with respect to age, sex, weight, left atrial size, LV ejection fraction, underlying cardiac disease, New York Heart Association class, duration of atrial fibrillation, and use of cardioactive drugs, including antiarrhythmic medications (Table 2).

Cardioversion Data

The first-shock cardioversion data for the 2 groups are summarized in Table 3. First-shock efficacy with the 70-J rectilinear biphasic waveform (60 of 88 patients, 68\%) was significantly greater than that with the 100-J damped sine wave monophasic waveform (16 of 77 patients, 21\%; \( P<0.0001 \)) (Figure 2). In addition, increased efficacy with the 70-J biphasic shocks was achieved with 50\% less delivered current (11\%\( \pm \)1 versus 22\%\( \pm \)4, \( P<0.0001 \)). No significant difference existed in the transthoracic impedance between the biphasic (76\%\( \pm \)17\%) and monophasic (78\%\( \pm \)16\%) waveform groups.

The cumulative cardioversion efficacy of the 100, 200, 300, and 360 J monophasic shocks was 21\%, 44\%, 68\%, and 79\%, respectively. In contrast, the cumulative cardioversion efficacy of the 70, 120, 150, and 170 J biphasic shocks was 68\%, 85\%, 91\%, and 94\%, respectively. The cumulative efficacy with the rectilinear biphasic waveform (83 of 88 patients, 94\%) was significantly greater than that with the damped sine wave monophasic waveform (61 of 77 patients, 79\%; \( P=0.005 \)) (Figure 2). Of note, the mean peak current delivered to patients with the 100-J monophasic shocks was equal to that delivered with 170-J rectilinear biphasic shocks (Table 1). Furthermore, 170-J biphasic shocks delivered \( \approx \)50\% less current than 360-J monophasic shocks.

Sixteen patients in the monophasic group could not be cardioverted with a maximal monophasic shock of 360 J. Eight of these patients (50\%) were successfully cardioverted with a 170-J biphasic shock. Five patients in the biphasic group could not be cardioverted with a maximal biphasic shock of 170 J. These patients received a 360-J monophasic shock, which was also unsuccessful in each patient. There were no complications associated with either the monophasic or biphasic shocks.

The cumulative cardioversion efficacy was significantly affected by the patient’s baseline transthoracic impedance (Figure 3). For patients with an impedance \( \leq 70 \) \( \Omega \), the

### Table 2. Patient Characteristics and Clinical Demographics

<table>
<thead>
<tr>
<th></th>
<th>Biphasic</th>
<th>Monophasic</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>88 (53)</td>
<td>77 (47)</td>
</tr>
<tr>
<td>Age, y</td>
<td>65( \pm )12</td>
<td>66( \pm )12</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>29 (33)</td>
<td>21 (27)</td>
</tr>
<tr>
<td>Male</td>
<td>59 (67)</td>
<td>56 (73)</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>89( \pm )21</td>
<td>93( \pm )24</td>
</tr>
<tr>
<td>Left atrial size, cm</td>
<td>4.7( \pm )1.0</td>
<td>4.6( \pm )0.8</td>
</tr>
<tr>
<td>LV ejection fraction, %</td>
<td>50( \pm )14</td>
<td>48( \pm )14</td>
</tr>
<tr>
<td>Transthoracic impedance, ( \Omega )</td>
<td>78( \pm )16</td>
<td>76( \pm )17</td>
</tr>
<tr>
<td>Heart disease</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>22 (25)</td>
<td>24 (31)</td>
</tr>
<tr>
<td>Coronary artery and valvular disease</td>
<td>7 (8)</td>
<td>7 (9)</td>
</tr>
<tr>
<td>Valvular disease</td>
<td>18 (21)</td>
<td>13 (18)</td>
</tr>
<tr>
<td>Idiopathic cardiomyopathy</td>
<td>3 (3)</td>
<td>8 (18)</td>
</tr>
<tr>
<td>Hypertension</td>
<td>7 (8)</td>
<td>3 (4)</td>
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<tr>
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</tr>
<tr>
<td>None</td>
<td>31 (35)</td>
<td>21 (27)</td>
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<tr>
<td>NYHA class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>59 (67)</td>
<td>47 (61)</td>
</tr>
<tr>
<td>II</td>
<td>23 (26)</td>
<td>27 (35)</td>
</tr>
<tr>
<td>III</td>
<td>4 (5)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>IV</td>
<td>2 (2)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Atrial fibrillation duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \leq 48 \text{ hours} )</td>
<td>15 (17)</td>
<td>15 (19)</td>
</tr>
<tr>
<td>&gt;48 hours( \leq 6 \text{ months} )</td>
<td>64 (73)</td>
<td>47 (61)</td>
</tr>
<tr>
<td>&gt;6 months</td>
<td>9 (10)</td>
<td>12 (16)</td>
</tr>
<tr>
<td>Unknown</td>
<td>0 (0)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Previous electrical cardioversion</td>
<td>37 (42)</td>
<td>28 (36)</td>
</tr>
</tbody>
</table>

| Medications     |          |            |
| ACE inhibitor   | 23 (26)  | 23 (30)    |
| Amiodarone      | 24 (27)  | 18 (23)    |
| \( \beta \)-Blocker | 41 (47) | 35 (45)    |
| Calcium-channel blocker | 27 (31) | 26 (33)   |
| Digoxin         | 38 (43)  | 35 (45)    |
| Diuretic        | 19 (22)  | 21 (27)    |
| Nitrate         | 5 (6)    | 6 (8)      |
| Type IA antiarrhythmic | 6 (7) | 7 (9)   |
| Type IC antiarrhythmic | 4 (5) | 1 (1)  |
| Sotalol         | 8 (9)    | 6 (8)      |

Values are mean\( \pm \)SD or n (%). NYHA indicates New York Heart Association. \( P=NS \) for all comparisons between monophasic and biphasic groups.
cumulative efficacy of the biphasic waveform (29 of 29 patients, 100%) was equivalent to that of the monophasic waveform (27 of 28 patients, 96%; \( P = \text{NS} \)). In contrast, in patients with an impedance \( > 70 \ \Omega \), the cumulative efficacy of the biphasic waveform (53 of 58 patients, 91%) was significantly greater than that of the monophasic waveform (30 of 44 patients, 68%; \( P = 0.004 \)). Compared with patients with an impedance \( \leq 70 \ \Omega \) (60±8 \( \Omega \)), patients with an impedance \( > 70 \ \Omega \) (86±12 \( \Omega \)) were heavier (98±24 versus 78±12 kg, \( P < 0.0001 \)) and had a larger left atrium (4.8±1.0 versus 4.5±0.8 cm, \( P = 0.04 \)). However, no significant differences existed in weight, duration of atrial fibrillation, left atrial size, LV ejection fraction, and transthoracic impedance between patients treated with the monophasic and biphasic waveforms in either the \( \leq 70 \) or \( > 70 \) \( \Omega \) groups.

Use of a biphasic waveform (\( P = 0.005 \)), patient weight (\( P = 0.002 \)), and baseline transthoracic impedance (\( P = 0.005 \)) were univariate predictors of successful cardioversion (Table 4). In addition, a trend toward a lower success rate was observed in patients with a longer duration of atrial fibrillation (\( P = 0.08 \)). Multivariate logistic regression identified 3 variables independently associated with cardioversion success: they were shock waveform used for cardioversion (\( P = 0.02 \)), baseline transthoracic impedance (\( P = 0.01 \)), and duration of atrial fibrillation (\( P = 0.02 \)). The adjusted relative risks (95% confidence intervals) for cumulative efficacy were 4.2 (1.3, 13.9) for use of a biphasic shock waveform, 0.64 (0.46, 0.90) for each 10-\( \Omega \) increase in transthoracic impedance, and 0.98 (0.97, 0.99) for each additional 30-day period of atrial fibrillation (Table 5).

**Discussion**

The principal finding of this study is that rectilinear biphasic shocks are significantly more effective than damped sine wave monophasic shocks for the transthoracic cardioversion of atrial fibrillation. Use of a rectilinear biphasic waveform was the most significant independent predictor of successful cardioversion. In addition to increased efficacy, rectilinear biphasic shocks could cardiovert with markedly less delivered current. The advantage of biphasic shocks was most pronounced in patients with a transthoracic impedance \( > 70 \ \Omega \).

In the 3 decades since the introduction of transthoracic electrical cardioversion, 2 alternative nonpharmacological approaches have been introduced for patients who fail the conventional cardioversion of atrial fibrillation: dual external defibrillators using an orthogonal electrode array, resulting in a 720-J defibrillator discharge,\(^3\) and internal catheter-based cardioversion.\(^4\) The limitations of these alternatives include potential muscular damage from high-energy shocks\(^3\) and the attendant inconvenience and risks of the invasive internal approach. More recently, it has been suggested that the cardioversion efficacy of damped sine wave monophasic shocks can be improved with ibutilide pretreatment.\(^21\) However, this approach is limited by the increased cost associated with the use of ibutilide and the cost and inconvenience of 3 to 4 hours of continuous electrocardiographic monitoring.
Most currently available defibrillators use a damped sine wave monophasic waveform, which is not impedance-compensated. Although the operator is required to select a particular energy setting, it is known that transthoracic current is a more precise descriptor of defibrillation threshold.

Because at a given energy setting the current delivered is dependent on transthoracic impedance, excessive current may be delivered to patients with low transthoracic impedance (increased toxicity), and insufficient current may be delivered to patients with high impedance (decreased efficacy). In fact, in this study, higher baseline transthoracic impedance was an independent predictor of shock failure.

In contrast to the damped sine wave monophasic waveform, the rectilinear biphasic waveform is advantageous in high-impedance patients because it is relatively insensitive to changes in transthoracic impedance. This is because of impedance compensation, which ensures a constant current in the first phase. For example, the peak current delivered to a patient with a 125-Ω impedance from a monophasic shock is, on average, only 55% of that delivered to a patient with a 50-Ω impedance. In contrast, the peak current delivered by a biphasic shock to a patient with a 125-Ω impedance is, on average, 68% of that delivered to a patient with a 50-Ω impedance, thereby reducing the adverse effect of increased transthoracic impedance on delivered current. Consistent with this relationship was the increased efficacy of the rectilinear biphasic shocks observed in patients with an impedance >70 Ω. On the basis of the mean human transthoracic impedance of ~70 Ω, the increased efficacy of rectilinear biphasic shocks is pertinent to ~50% of patients undergoing cardioversion.

It is important to note that increased efficacy with rectilinear biphasic shocks was achieved with significantly lower delivered current than with monophasic shocks. Previous studies during ventricular defibrillation have demonstrated that biphasic shocks, which defibrillate with less delivered current, result in less post-shock myocardial dysfunction than monophasic shocks.

Prior Studies
Lown et al initially reported a cardioversion efficacy of ~90%; however, their patients differed significantly from the patients who undergo electrical cardioversion in the current era in that their patients were younger, most had rheumatic mitral valve disease, and many were receiving treatment with quinidine. In contrast, our patients were older, had a mixed cardiac origin of atrial fibrillation, and were receiving a variety of antiarrhythmic drugs, including amiodarone.

More recently, the reported efficacy of monophasic shocks for the cardioversion of atrial fibrillation has varied widely, ranging from 38% to 96%. This variation largely reflects differences in the baseline characteristics of patients selected for cardioversion. As in our study, prior studies have demonstrated that a longer duration of atrial fibrillation and an increased transthoracic impedance predict unsuccessful cardioversion. In this study, the superiority of the rectilinear biphasic waveform over the damped sine wave monophasic waveform was demonstrated in 2 groups who were similar at baseline with respect to variables reported to affect shock success, including weight, transthoracic impedance, and duration of atrial fibrillation.

Limitations
A potential limitation of this study is that it is not possible to extrapolate the benefit observed with the rectilinear biphasic waveform to other types of biphasic waveforms. In addition, it is unknown whether other types of monophasic waveforms, unrelated to a damped sine wave, would be associated with a higher success rate.

Conclusions
Rectilinear biphasic shocks have a significantly greater efficacy than damped sine wave monophasic shocks for the transthoracic electrical cardioversion of atrial fibrillation. Additionally, increased efficacy with rectilinear biphasic shocks is achieved with significantly less delivered current than with monophasic shocks. The combination of increased efficacy and decreased current requirements suggest that rectilinear biphasic shocks may be the preferred method for the transthoracic electrical cardioversion of atrial fibrillation.

Appendix
Investigators and Participating Institutions
Johns Hopkins University Medical Center, Baltimore, Md: Hugh Calkins, MD (principal investigator), Rozann Hansford, RN; Uni-
References


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