Double and Triple Sequential Shocks Reduce Ventricular Defibrillation Threshold in Dogs With and Without Myocardial Infarction

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The role of optimal placement of electrodes and mode of shock delivery from a defibrillator was examined in dogs with and without myocardial infarction. Single, double and triple truncated exponential shocks separated by 1 ms were delivered through various electrode combinations and cardiac vectors after electrical induction of ventricular fibrillation. A single shock through a pathway not incorporating the interventricular septum (catheter electrodes or epicardial patches between anterior and posterior left ventricle) required the highest total energy (22.6 and >26.4 J, respectively) and peak voltage (1,004 and >1,094 V, respectively) to terminate ventricular fibrillation. A single shock through a pathway including the interventricular septum required lower total energy and peak voltage to defibrillate.

Combinations of two sequential shocks between an intracardiac catheter electrode and anterior left ventricular epicardial patch, between the catheter electrode and subcutaneous extrathoracic plate and between three ventricular epicardial patches all significantly reduced total energy (7.7, 8.7 and 7.8 J, respectively) and peak voltage (424, 436 and 424 V, respectively) needed to defibrillate. Three sequential shocks exerted no significant additional reduction in total energy of the defibrillation threshold than did two sequential shocks. Infarcted canine heart required less peak voltage but not total energy to terminate ventricular fibrillation than did noninfarcted heart. Therefore, two sequential shocks over different pathways reduce both total energy and peak voltage required to terminate ventricular fibrillation.

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artery distal to its first diagonal branch was isolated from descending coronary artery (Fig. 1). The wires were tunneled out to the skin. The left anterior descending coronary artery about 5 mm from the ventricular base, with the long axis parallel to and about 5 mm from the left anterior descending coronary artery (Fig. 1). The wires were tunneled out to the skin. The left anterior descending coronary artery distal to its first diagonal branch was isolated from the surrounding tissue and occluded using a Harris two-stage procedure (4). Two hours after complete occlusion, the ligature was released and arterial blood flow was restored. Intravenous lidocaine (2 mg/kg) was administered 5 minutes before reperfusion. While intrapleural air was being evacuated by a vacuum pump, the chest was closed in layers and the dog was allowed to recover. The wound was closed, the dog was dressed in a vest and the electrode leads were placed in a pocket contained in the vest. Routine postoperative care by a veterinarian was given and included antibiotic (cefazolin sodium) and analgesic agents.

Study procedure. Four to 14 days after myocardial infarction, dogs were anesthetized with intravenous secobarbital (30 mg/kg), intubated and ventilated with room air using a volume-cycled respirator (Harvard, model 607). A left thoracotomy at the fourth intercostal space was performed using sterile technique, and the pericardium was opened and sewn to the wound edges to support the heart. Two pairs of Teflon-coated wire electrodes were sutured to the left ventricular surface for electrocardiographic monitoring and alternating current-induced fibrillation. An epicardial patch electrode (40 × 18 or 52 × 30 mm) was sewn to the anterior left ventricle about 5 to 10 mm from the ventricular base, with the long axis parallel to and about 5 mm from the left anterior descending coronary artery (Fig. 1). The wires were tunneled out to the skin. The left anterior descending coronary artery distal to its first diagonal branch was isolated from the surrounding tissue and occluded using a Harris two-stage procedure (4). Two hours after complete occlusion, the ligature was released and arterial blood flow was restored. Intravenous lidocaine (2 mg/kg) was administered 5 minutes before reperfusion. While intrapleural air was being evacuated by a vacuum pump, the chest was closed in layers and the dog was allowed to recover. The wound was closed, the dog was dressed in a vest and the electrode leads were placed in a pocket contained in the vest. Routine postoperative care by a veterinarian was given and included antibiotic (cefazolin sodium) and analgesic agents.

Study procedure. Four to 14 days after myocardial infarction, dogs were anesthetized with intravenous secobarbital (30 mg/kg), intubated and mechanically ventilated at a rate and tidal volume indicated from a nomogram. Arterial partial pressure of oxygen (PO2) and pH were monitored and kept within normal limits by varying respiratory rate or volume or by giving sodium bicarbonate. Secobarbital (4 to 6 mg/kg) was repeated as necessary to maintain anesthesia. No data were collected for 15 minutes after anesthesia administration. The right femoral artery and vein were cannulated. The arterial catheter was connected to a Statham pressure transducer (P23 Db) to monitor blood pressure. A subcutaneous titanium plate (76 × 48 × 0.7 mm) was placed extrathoracically in the fourth left intercostal space overlying the cardiac apex.

A 9.5F electrode catheter (Medtronic 6880), specially designed for cardioversion and defibrillation, was inserted through the right external jugular vein and advanced to the right ventricular apex under fluoroscopic control. The catheter has two bipolar pairs of electrodes that have a surface area of 2.5 cm2/pair. The distance between two pairs of electrodes was 75 or 100 mm. The distal pair of electrodes was in the right ventricular apex and the proximal pair was at the superior vena cava-right atrial junction. When the defibrillating shock was delivered over the catheter, the two distal electrodes in the right ventricle were coupled together electrically and served as the cathode, and the proximal electrodes coupled together served as the anode. The catheter position was considered satisfactory if the right ventricular pacing threshold using the distal pair of electrodes was 3 mA or less with a rectangular stimulus of 2 ms duration. The location of the catheter tip was checked periodically by fluoroscopy and by retesting the pacing threshold. The catheter was repositioned if dislodgment resulted after defibrillating shocks.

The specially designed external power source (Medtronic model 2366) can deliver through two separate outputs two shocks separated by 1 ms that have a truncated exponential waveform with 63% tilt. The output of each shock can be changed from 0 to 1,090 V in 10 V steps. For each pair of shocks, the voltage of the second shock equalled that of the first. Because electrode impedance varied as the electrode combination changed, pulse duration ranged from 3 to 6 ms.

Dogs Without Myocardial Infarction (Group II)

Experimental preparation. Healthy mongrel dogs of either sex, weighing 14 to 25 kg, were prepared using the same study procedure as in Group I dogs, but without myo-
cardiac infarction. After a left thoracotomy, three epicardial patch electrodes (52 × 30 mm) were sewn to the anterior and posterior left ventricle and anterior right ventricle (Fig. 1). The left ventricular electrodes were placed 5 to 10 mm from the ventricular base, with the long axis parallel to and about 5 mm from the left anterior descending and posterior descending coronary arteries. The anterior right ventricular epicardial patch electrode was placed equidistant to the anterior and posterior left ventricular epicardial patch electrodes. Two pairs of Teflon-coated wire electrodes were sutured on the left ventricle. The wires were tunneled out to the skin. The wound was closed, and the vital signs were monitored as in the previous study. The Medtronic 6880 electrode catheter with an interelectrode distance of 100 mm was inserted to the right ventricular apex. The position of the catheter was checked periodically as in the previous study.

**Study procedure.** Two external power sources (Medtronic model 2376) were used with each source designed to deliver two separate outputs with 1 ms between shocks that had a 5 ms closed exponential waveform. When three sequential shocks were required, the two power sources were synchronized in series so that the trailing edge of the second shock delivered from one source was separated by 1 ms from the leading edge of the third shock delivered from the other source. Because the pulse duration was fixed, the tilt varied from 60 to 80% as the impedance changed. The voltage of all three shocks was the same.

**Defibrillation Protocol for Group I and Group II**

**Induction and termination of ventricular fibrillation.** Ventricular fibrillation was induced by 60 Hz alternating current (20 mA) applied for 5 seconds by means of one pair of electrodes sewn to the ventricle. Ten seconds after induction of fibrillation, the first defibrillating test shock was delivered. The delivered waveforms were recorded on a digital oscilloscope (Smartscope model 2220), and the voltage (V) of the leading edge (V1) and the trailing edge (V2) of each shock was measured in the Group I study. Output from the defibrillators in the Group II study was interfaced to a Tektronix 5113 oscilloscope to record both the voltage and current (in amperes) of the leading (I1) and trailing (I2) edges to allow calculations of energy and resistance. The waveform of the shocks in the Group I dogs had a constant tilt at 63%. The energy (E), resistance (R) and peak current (I0) of these shocks were calculated by the following equation: 

$$E = \frac{1}{2} \times \text{capacitance} \times (V_0^2 - V_1^2).$$

Capacitance used in this study was 50 μF. Because current was monitored in the Group II study, the energy of the shocks used in the Group II study was calculated by the following equation: 

$$E = \text{pulse duration (seconds)} \times (V_{0,I0} - V_{1,I0})/\ln (V_{0,I0}/V_{1,I0}).$$

Impedance (ohms) was calculated by equation: 

$$R = \frac{(V_{0,I0} - V_{1,I0})}{\ln (V_{0,I0}/V_{1,I0})}.$$ 

If the first voltage chosen terminated ventricular fibrillation, the latter was reintimated 5 minutes later and the voltage of the following shocks was progressively reduced by 10% until a voltage was reached that failed to defibrillate. If the first voltage chosen did not terminate ventricular fibrillation, a suprathreshold (50 to 80 J) rescue shock was given extrathoracically. Ventricular fibrillation was reintitated 5 minutes later, and a shock with a voltage 10% greater than the initial shock was delivered. The initial voltage chosen to test for ventricular fibrillation termination for a single shock was estimated from the dog's body weight (approximately 38 V/kg body weight) (5). The steps were repeated until defibrillation resulted. Defibrillation threshold was defined as the shock strength that terminated ventricular fibrillation, but that was no more than 10% greater than a shock that failed to defibrillate the ventricle on at least two trials (6).

**Combination shocks.** During each combination of shocks, the following electrodes were used (Fig. 1).

- **Right ventricular apex (RV apex):** cathode composed of the distal pair of electrodes on the Medtronic 6880 endocardial catheter situated in the right ventricular apex inserted at the time of surgery immediately before study.
- **Superior vena cava (SVC):** anode composed of the proximal pair of electrodes on the Medtronic 6880 intracardiac catheter situated at the superior vena cava-right atrial junction.
- **Anterior left ventricle (LVa):** cathode or anode composed of an epicardial patch electrode sewn on the anterior left ventricle at the time of surgery.
- **Posterior left ventricle (LVp):** anode composed of an epicardial patch electrode sewn on the posterior left ventricle at the time of surgery.
- **Anterior right ventricle (RVa):** cathode or anode composed of an epicardial patch electrode sewn on the anterior right ventricle at the time of surgery.
- **Subcutaneous (SC):** anode composed of a subcutaneous titanium electrode placed extrathoracically overlying the cardiac apex.

**Group I**

For the dogs in the Group I study, eight combinations of shocks were studied in random order.

**Single shocks.** **Pathway 1 (A):** a single shock delivered through the catheter electrodes to provide control values for a standard method of shock delivery.

**Pathway 2 (B):** a single shock delivered between the right ventricular apical endocardial electrode (cathode) and the anterior left ventricular epicardial electrode (anode) to determine whether epicardial placement of one electrode reduced the defibrillation threshold.
Pathway 3 (C): a single shock delivered between the right ventricular apical endocardial electrode (cathode) and the subcutaneous plate (anode) to determine whether subcutaneous placement of one electrode reduced the defibrillation threshold (analogous to pathway 2 [B] but avoiding thoracotomy).

Pathways 1 + 2 (D): a single shock delivered between the right ventricular apical endocardial electrode (cathode) and two anodes, one in the superior vena cava and the other over the anterior left ventricular epicardium, to determine whether a single shock delivered simultaneously over different cardiac vectors reduced the defibrillation threshold.

Pathways 1 + 3 (E): a single shock delivered between the right ventricular apical endocardial electrode (cathode) and two anodes, one in the superior vena cava and the other in the subcutaneous position, to determine whether a single shock delivered simultaneously over different cardiac vectors reduced the defibrillation threshold.

Pathways 1 + 2 (G): two sequential shocks, with the first shock delivered over the catheter electrodes, followed by a second shock delivered between the right ventricular apical endocardial electrode of the catheter (cathode) and the anterior left ventricular epicardial patch (anode) to determine whether two sequential shocks delivered over different cardiac vectors reduced the defibrillation threshold.

Pathways 1 + 3 (H): two sequential shocks, with the first shock delivered over the catheter electrodes, followed by a second shock delivered between the right ventricular apical endocardial electrode of the catheter (cathode) and the subcutaneous electrode (anode) to determine whether two sequential shocks delivered over different cardiac vectors reduced the defibrillation threshold (analogous to two sequential shocks with pathways 1 + 2 [G], but avoiding thoracotomy).

Group II

Six combinations of shocks were studied in a random order in the Group II dogs.

Single shocks. Pathway 4 (I): a single shock delivered between the anterior (cathode) and posterior left ventricular epicardial patch (anode) electrodes to determine whether a single shock delivered over left ventricular epicardial electrodes reduced the defibrillation threshold.

Pathway 5 (J): a single shock delivered between the anterior left (cathode) and right (anode) ventricular epicardial electrodes to determine whether a single shock delivered by way of a different cardiac vector that presumably included the mass of the interventricular septum reduced the defibrillation threshold.

Pathway 6 (K): a single shock delivered between the anterior right (cathode) and posterior left (anode) ventricular epicardial electrodes to determine whether a single shock delivered by way of a different cardiac vector reduced the defibrillation threshold.

Two shocks. Pathways 1 + 2 (G): Two sequential shocks delivered over pathways 1 + 2 were used to compare values in dogs with and without myocardial infarction.

Pathways 5 + 4 (L): two sequential shocks, with the first shock delivered between the anterior left (cathode) and right (anode) ventricular epicardial electrodes, followed by a shock delivered between the left anterior (cathode) and posterior (anode) epicardial electrodes to determine whether two sequential shocks delivered by way of different cardiac vectors reduced the defibrillation threshold.

Three shocks. Pathways 1 + 2 + 7 (M): three sequential shocks with the first shock delivered over the catheter electrodes, the second shock between the right ventricular apical endocardial electrode of the catheter (cathode) and anterior left epicardial electrode (anode) and a third shock delivered between the right ventricular apical endocardial electrode of the catheter (cathode) and left posterior epicardial (anode) to determine whether three sequential shocks delivered over the different cardiac vectors reduced the defibrillation threshold.

Data Analyses

The data are expressed as mean ± 1-standard deviation. In the Group I study, total delivered energy (E) and peak voltage (V₀) to defibrillate were used for comparison. The total delivered energy, peak voltage and current (I₀) of defibrillation were used for comparison in the Group II study. In the case of two and three sequential shocks, two and three capacitances were used; hence, the mean V₀ and I₀ of two and three individual shocks were shown and used to compare the difference. Energy for the sequential shocks, however, was expressed as the sum of the energy of the multiple individual shocks. Impedances of each pathway were calculated between two electrodes for each shock.

The difference in mean value was analyzed using a t test adjusted for multiple comparison by the Bonferroni method (7). Analysis of covariance was used to compare voltage and energy levels while adjusting for differences in body weight and number of shocks. Linear regression analyses were used to assess the relation among voltage, current and energy, body weight and number of shocks. A probability (p) value of less than 0.05 was considered statistically significant.

Results

Defibrillation Thresholds of Dogs With Myocardial Infarction

Study group. Fifteen dogs survived the left anterior descending coronary artery ligation-reperfusion procedure.
In one of these dogs, marked hypotension developed after 21 trials of defibrillation, and in another two dogs, single pulse shocks through the catheter electrode with the maximal output (1,090 V) failed to terminate ventricular fibrillation. Therefore, the remaining 12 dogs constituted the study group. Body weight ranged from 15 to 27 kg (mean 21.7 ± 3.9). In 1 dog, the 75 mm interelectrode distance was used, and in the remaining 11 dogs, the interelectrode distance was 100 mm. In three dogs, an epicardial patch of medium size (40 x 18 mm) was used, and in the remaining nine dogs, a larger patch (52 x 30 mm) was used. Because defibrillation threshold did not differ between dogs with medium-sized epicardial patches and those with large patches or between those with 75 and 100 mm spacing between electrodes, data from 12 dogs were analyzed as a single group. The total number of defibrillation trials ranged from 20 to 74 (mean 41.8 ± 17.7).

**Defibrillation thresholds.** The peak voltage required to terminate ventricular fibrillation is summarized in Figure 2. Peak voltage of the leading edge (V_o) for single shocks through the catheter electrodes (pathway 1) was significantly greater than all other combinations. There was no significant difference in the V_o required to terminate ventricular fibrillation between the single shock delivered over a single pathway (pathway 2 versus 3) or simultaneously over two pathways (pathways 1 + 2 versus 1 + 3). The V_o was significantly greater for two sequential shocks, both delivered over pathway 1 compared with two sequential shocks delivered between the intracardiac electrodes and an epicardial patch (pathways 1 + 2) or between the intracardiac electrodes and the subcutaneous plate (pathways 1 + 3). The values for V_o of two sequential shocks for pathways 1 + 2 and 1 + 3 were not significantly different from each other. The V_o for sequential shocks was significantly less than that for a single shock (pathways 1 + 1 versus 1, pathways 1 + 2 and 1 + 3 versus 1, 2 and 3).

*Defibrillation thresholds (in joules) are presented in Figure 3. A single shock over catheter electrodes (pathway 1) and two sequential shocks delivered over catheter electrodes alone required significantly more energy to defibrillate than did other electrode combinations. Although two sequential shocks delivered over pathways 1 + 2 required the lowest energy for defibrillation, the difference was not statistically significant when compared with a single shock delivered over one pathway (pathways 2 and 3), a single shock delivered simultaneously over two pathways (pathways 1 + 2 and 1 + 3) and two sequential shocks delivered over two pathways (pathways 1 + 3). When a single shock delivered over a single pathway (pathway 2), a single shock delivered simultaneously over two pathways (pathways 1 + 2) and two sequential shocks delivered over two pathways (pathways 1 + 2) using combinations of the catheter electrode and epicardial patch electrode were compared, sequential shocks (pathways 1 + 2) required the lowest total energy for defibrillation. Of these three combinations, a single shock over a single pathway between the catheter and epicardial patch electrodes (pathway 2) required the highest energy for defibrillation, although the difference did not reach statistical significance. When the subcutaneous plate was substituted for the epicardial patch electrode (a single shock delivered over pathway 3 and pathways 1 + 3 and two sequential shocks delivered over pathways 1 + 3), there were no differences between required energy levels.*

**Relation among defibrillation thresholds, body weight and number of defibrillation trials.** The defibrillation threshold voltage (V_o), current (I_o) and energy (E) correlated

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**Figure 2.** Peak voltages at defibrillation threshold for various electrode combinations for Group I dogs (with infarction). N = number of cases studied. See text for definition of pathways A to H. Single shock over one pathway (□); single shock over two pathways (■); two sequential shocks over one pathway (□); two sequential shocks over two pathways (□). A > B = C = D = E = F > G = H, C = H; p < 0.05.
significantly with body weight (Fig. 4). Heavier dogs required more voltage, energy and calculated current to terminate ventricular fibrillation ($r = 0.361$, $p = 0.0026$ for $V_o$; $r = 0.447$, $p = 0.0014$ for $E$; $r = 0.279$, $p = 0.022$ for $I_o$ [not presented]). This correlation holds despite the changes in current pathways and the changes from a single shock to double shocks.

The number of defibrillation shocks did not relate to either the voltage or total energy of the defibrillation threshold ($p = 0.3$ for $V_o$; $p = 0.11$ for $E$).

**Defibrillation Thresholds of Dogs Without Myocardial Infarction**

**Study group.** Twenty-eight dogs were prepared for the Group II study. Eight of the 28 dogs either developed hypotension or required prolonged resuscitation after an unsuccessful trial of defibrillation (pathway 4), between anterior and posterior ventricular epicardial electrodes). Therefore, only the remaining 20 dogs were included in this study. In all dogs defibrillation was successfully accom-
plished using two or more electrode combinations. All combinations were tested, but not all resulted in defibrillation using pathway 4, which required a much higher energy to terminate ventricular fibrillation than did the other electrode combinations. The data points of peak voltage ($V_o$) and current ($I_o$) for pathway 4 were taken for statistical analyses, either at the minimal voltage and current of successful defibrillation or at the voltage and current that failed to defibrillate at the maximal voltage setting of the external power source. The rate of successful defibrillation using pathway 4 at the maximal defibrillator setting of 1,090 volts was only 37%. Therefore, the actual mean defibrillation threshold for pathway 4 was higher than the data shown. In all dogs, the catheters with 100 mm distance between electrode pairs and the large size patch electrode (52 × 30 mm) were used in this study. Total number of defibrillation trials ranged from 19 to 47 (mean 31.1 ± 5.9).

**Defibrillation thresholds.** Voltages at defibrillation thresholds are summarized in Figure 5. Peak voltage of the leading edge ($V_o$) for a single shock delivered over pathway 4 was significantly greater than that for all other electrode combinations. The $V_o$ for a single shock with current paths that crossed the interventricular septum (pathways 5 and 6) was significantly less than that of the shock with a current pathway that did not pass through the interventricular septum (pathway 4), but $V_o$ was the same for pathways 5 and 6. The $V_o$ for two sequential shocks delivered over a combination of catheter and anterior left ventricular epicardial electrodes (pathways 1 + 2) was greater than that for sequential shocks delivered over epicardial patch electrodes (pathways 5 + 4), but the difference did not reach statistical significance. The $V_o$ for two sequential shocks (pathways 1 + 2 and 5 + 4) was significantly less than that for a single shock (pathways 4, 5 and 6). The $V_o$ for three sequential shocks (pathways 1 + 2 + 7) was significantly less than the $V_o$ for a single shock (pathways 4, 5 and 6) and that for two sequential shocks delivered over pathways 1 + 2, but the difference between pathways 1 + 2 + 7 and 5 + 4 did not reach statistical significance.

Currents at defibrillation thresholds ($I_o$) are summarized in Figure 6. A single shock delivered over pathway 4 required significantly more current (>13.7 A) than did other electrode combinations. The $I_o$ for a single shock delivered over a pathway including the interventricular septum (pathways 5 and 6) was significantly less than that for a single shock delivered over a pathway that did not cross the septum (pathway 4). The $I_o$ for two sequential shocks (pathways 1 + 2 and 5 + 4) was significantly less than that for a single shock (pathways 4, 5 and 6). There was no statistical difference in the $I_o$ between sequential shocks delivered over pathways 1 + 2 and that delivered over pathways 5 + 4. The $I_o$ for three sequential shocks was significantly less than that for single shocks (pathways 4, 5 and 6), but not for two sequential shocks (pathways 1 + 2 and 5 + 4).

**Total energies required for defibrillation are summarized in Figure 7.** A single shock delivered over pathway 4 required the highest energy for defibrillation (>26.5 J). Two and three sequential shocks (pathways 1 + 2, 5 + 4 and 1 + 2 + 7) required defibrillation energies of 6.5, 7.7 and 7.3 J, respectively, while a single shock delivered over pathways 5 and 6 required energies of 13.6 J. Compared with a single shock delivered over pathway 4, multiple

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**Figure 5.** Peak voltages at defibrillation threshold for different electrode combinations for Group II dogs (without infarction). See text for definition of pathways I to M. Symbols as in Figure 5. I > J = K > G = L = M; p < 0.05.

**Figure 6.** Peak currents at defibrillation threshold for different electrode combinations for Group II dogs (without infarction). See text for definition of pathways I to M. Symbols as in Figure 5. I > J = K > G = L = M; p < 0.05.
shocks reduced energy by 73% (p < 0.05), and single shocks delivered over pathways 5 and 6 reduced energy by 47% (p < 0.05).

The body weight and number of defibrillation trials did not alter the voltage, current or total energy (E) at defibrillation threshold (p = 0.35 for V₀, p = 0.36 for I₀, p = 0.18 for E).

Impedances between the electrodes of current pathways. The impedance between electrodes on the catheter (pathway 1) was significantly greater than for all other combinations (p < 0.05) (Fig. 8). The impedances for pathways 2, 5 and 6 were not different statistically but exceeded that for pathway 7 (p < 0.05). The impedance of pathway 4 was not different from that of pathways 2, 6 and 7 but was significantly less than that of pathway 5. The resistance of the pathways did not relate to the peak voltage or total energy of the defibrillation threshold (p > 0.1).

Comparison Between Dogs in Group I and Group II (Table 1)

Body weight, number of defibrillation trials and voltage and total energy at defibrillation threshold (Table 2). These were compared between groups with the same electrode combination (pathways 1 + 2). The body weight of Group I dogs was significantly greater than that of Group II dogs (p = 0.023). The peak voltage and total energy at defibrillation threshold were compared by analysis of covariance, with body weight as covariate. The voltage (V₀) to terminate ventricular fibrillation in dogs without infarction (Group II) was significantly greater than that in dogs with infarction (Group I) (p = 0.025). The energy values adjusted for body weight differences were not significantly different (p = 0.18). The differences in total energy levels at defibrillation threshold adjusted for body weight and number of shocks between the two groups did not reach statistical significance, but the peak voltage to terminate ventricular fibrillation in normal hearts remained significantly greater than that of hearts with subacute infarction (p = 0.02).

Adjusted voltage at defibrillation threshold (V₀) for both Group I and Group II dogs (Fig. 9). The adjusted V₀ of a single shock delivered over the current pathways not crossing the interventricular septum (pathways 1 and 4) was significantly greater than that of all other single shock combinations. The adjusted voltage of two sequential shocks (pathways 1 + 2, 1 + 3 and 5 + 4) was significantly less than that of single shocks (pathways 1, 2, 3, 4, 5, 6, 1 + 2 and 1 + 3), except for that of two sequential shocks delivered over catheter electrodes alone (pathways 1 + 1). Two sequential shocks delivered to catheter electrodes alone

Figure 7. Total energies at defibrillation threshold for different electrode combinations for Group II dogs (without infarction). See text for definition of pathways I to M. Symbols as in Figure 5. I > J = K > G = L = M; p < 0.05.

Figure 8. Comparison of impedances between current pathways in Group II dogs (without infarction). 1 > 2 = 5 = 6 > 7; 4 = 2, 6, 7; 4 < 5; p < 0.05.
required less adjusted voltage than that of a single shock using the same pathway (pathways 1 + 1 versus 1), but more voltage than that required for all other sequential shock pathways. Three sequential shocks required significantly less peak voltage than did two sequential shocks (pathways 1 + 2 + 7 versus 1 + 2, 1 + 3 and 5 + 4).

Adjusted total energy at defibrillation threshold for both Groups I and II (Fig. 10). A single shock delivered along a current pathway not including the interventricular septum (pathways 1 and 4) required more energy to terminate ventricular fibrillation than did all other combinations. When a single shock was delivered over a current

Table 1. Characteristics of Group I and Group II Dogs

<table>
<thead>
<tr>
<th>Features of Difference</th>
<th>Group I (with infarction)</th>
<th>Group II (without infarction)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of dogs</td>
<td>12</td>
<td>20</td>
<td></td>
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<tr>
<td>Body weight (kg)</td>
<td>15 to 27</td>
<td>14 to 22</td>
<td>&lt;0.001</td>
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<tr>
<td>Mean</td>
<td>(21.7 ± 3.9)</td>
<td>(18.9 ± 2.4)</td>
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<tr>
<td>No. of shock trials</td>
<td>20 to 74</td>
<td>19 to 47</td>
<td>&lt;0.001</td>
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<tr>
<td>Mean</td>
<td>(41.8 ± 17.7)</td>
<td>(31.1 ± 5.9)</td>
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</tr>
<tr>
<td>Duration of MI (days)</td>
<td>4 to 14</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>(7 ± 3.1)</td>
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<tr>
<td>Size of epicardial patch electrode (cm)</td>
<td>4.0 × 1.8 (3)*</td>
<td>5.2 × 3.0 (9)*</td>
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<td>Interelectrode distance of catheter (mm)</td>
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<td>100 (11)*</td>
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<td>External power source</td>
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<td>Medtronic 2376</td>
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<td>Wave form of shock</td>
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<td>Data recorded</td>
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<td>Vm, Vs, Ls, Ir</td>
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<tr>
<td>Equation of energy calculation</td>
<td>E = ( \frac{1}{2} C[V_v^2 - V_f^2] )</td>
<td>E = ( d[\ln(V_s/L_s - V_d)]/\ln(V_s/L_s) )</td>
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</tbody>
</table>

Numbers in parentheses indicate number of cases. C = capacitance; d = shock duration; E = energy; Ls = leading edge of current; Ir = trailing edge of current; ln = natural log; MI = myocardial infarction; Vf = trailing edge of voltage; Vs = leading edge of voltage.

Table 2. The Different Features of Studies in Group I and Group II Dogs With Two Sequential Shocks (pathways 1 + 2)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Group I</th>
<th>Group II</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of dogs</td>
<td>12</td>
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<td>Body weight (kg)</td>
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<td>Number of defibrillation trials</td>
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<tr>
<td>Vp</td>
<td>408 ± 117.8</td>
<td>437.1 ± 90.7</td>
<td>NS</td>
</tr>
<tr>
<td>E</td>
<td>7.9 ± 4.2</td>
<td>8.8 ± 3.6</td>
<td>NS</td>
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<tr>
<td>Vp*</td>
<td>375</td>
<td>465</td>
<td>0.025</td>
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<tr>
<td>E*</td>
<td>6.8</td>
<td>8.7</td>
<td>0.18</td>
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<tr>
<td>Vp+</td>
<td>412</td>
<td>434</td>
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<tr>
<td>E+</td>
<td>8.0</td>
<td>7.7</td>
<td>0.84</td>
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<tr>
<td>Vp+</td>
<td>365</td>
<td>474</td>
<td>0.02</td>
</tr>
<tr>
<td>E+</td>
<td>6.4</td>
<td>9.1</td>
<td>0.12</td>
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</table>

*Adjusted for body weight; †Adjusted for number of shocks; ‡Adjusted for body weight and number of shocks. E = total energy at defibrillation threshold; NS = not significant; Vp = peak voltage at defibrillation threshold.
pathway across the interventricular septum, dogs with myocardial infarction required less energy to defibrillate than did dogs without infarction (pathways 3, 1 + 2 and 1 + 3 versus 5 and 6) except for the pathway 2, which had greater variation within the group. Two sequential shocks delivered through the catheter alone (pathway 1) did not use less total energy than did a single shock, although the adjusted peak voltage of two sequential shocks delivered through the catheter alone was less than that of a single shock. The adjusted energy of two sequential shocks over two pathways was less than that of a single shock over one pathway in Group II dogs (no infarction) (pathways 1 + 2 and 5 + 4 versus pathways 4, 5 and 6), but not in Group I dogs (with infarction) (pathways 1 + 2 and 1 + 3 versus pathways 2

Figure 9. Comparison of peak voltages adjusted for body weight at defibrillation threshold between different electrode combinations for dogs in Groups I and II. See text for definition of pathways A to M. Symbols as in Figures 2 and 5. A = 1 > J = K = B = C = D = E = F > G = H = L > M; p < 0.05.

Figure 10. Comparison of total energies adjusted for body weight at defibrillation threshold between different electrode combinations for dogs in Groups I and II. See text for definition of pathways A to M. Symbols as in Figures 2 and 5. A = 1 = F > J = K = B; J = K > C = D = E = G = H = L = M; B = C, D, E, G, H, L, M; p < 0.05.
and 3). The adjusted energy of three sequential shocks was substantially less than that of single and double shocks, but the difference did not reach statistical significance.

Discussion

Major findings. Important new findings from the present study are that: 1) less energy and voltage are required to terminate ventricular fibrillation if the electrode pathway incorporates the interventricular septum; 2) sequential shocks delivered to the epicardium directly are as effective as when one of the electrodes is in the right ventricular apex; 3) three sequential shocks require less peak voltage but the same total energy as two sequential shocks; and 4) defibrillating a canine heart with a subacute myocardial infarction is no more difficult than defibrillating a normal canine heart.

Importance of including interventricular septum in electrode pathways. A single shock delivered over the electrode combinations that included the interventricular septum required significantly less peak voltage and total energy to defibrillate the infarcted and noninfarcted canine hearts than did the single shocks that did not include the interventricular septum. This might have been expected from previous studies from this laboratory (8), showing the importance of depolarizing a critical mass of myocardium. The interventricular septum obviously represents a large mass of ventricular myocardium that contributes to the fibrillation process.

Efficacy of two sequential shocks. Two sequential shocks separated by 1 ms delivered over two pathways reduced the defibrillation threshold energy as well as peak voltage by 60% when compared with a single shock delivered over the catheter electrode alone. Perhaps the defibrillation threshold for sequential shocks might have been reduced further had the shocks been closer together (9).

Efficacy of sequential shocks to reduce defibrillation threshold is controversial. Kugelberg (10) reported that two square wave pulses of 20 ms duration separated by 100 ms could defibrillate the heart at 20% of the total energy required for a single shock. Resnekov et al. (11) also showed a significant reduction in total energy using two trapezoidal pulses of 25 ms duration separated by 75 ms. However, subsequent studies (12–15) showed that two sequential shocks required a higher total energy to terminate ventricular fibrillation that did a single shock. These experiments (10–15) used a single lead system over which both single and sequential shocks were delivered. Our results also show that two sequential shocks delivered over the same electrode pair do not reduce the energy required to defibrillate. Data from previous studies (10–15) may not be completely comparable with ours because of differences in the waveform of shocks (half sinusoidal, square or trapezoidal), duration of each shock, separation time between shocks or number and position of defibrillating electrodes (endocardial, epicardial or transthoracic). However, two sequential shocks required less peak current to terminate ventricular fibrillation than did a single shock in each of these studies (13–15). Recently Jones et al. (16) showed a significant reduction in total energy to terminate ventricular fibrillation in pigs by two sequential shocks separated by 1 ms that were delivered through a catheter electrode and epicardial patch in the present study (pathways 1 + 2).

Defibrillation threshold of two sequential shocks obtained with the epicardial patch of subcutaneous plate from the previous study did not differ significantly for voltage or total energy, suggesting that these modes are comparable. These findings are important for the sequential shock approach because they indicate that an epicardial electrode and, therefore, a thoracotomy may be avoided (17).

However, we also found that when epicardial patch electrodes (pathways 5 + 4) were used for both shocks, without an intracavitary electrode, two sequential shocks still reduced the defibrillation threshold peak voltage by 75% when compared with a single shock delivered over patches on the anterior and posterior current pathways that included the interventricular septum (pathways 5 and 6). The importance of these findings is that in a patient who requires cardiac surgery along with defibrillator implantation, sequential shocks delivered only over an epicardial electrode may be employed and an intravascular lead is unnecessary.

The significant reduction in total energy and peak voltage by sequential shocks delivered over a dual electrode system in our study may be explained by several factors. First, impedance of muscle exceeds that of blood (18), allowing some shunting of current over intracardiac blood instead of traversing the myocardium when the shock is delivered through the catheter electrode alone. An epicardial patch or subcutaneous plate may help reduce total energy and peak voltage when compared with a single shock through a catheter electrode (19). Second, current density is higher near the electrodes (16). Two different lead orientations, therefore, may increase the volume of myocardium receiving higher current density and depolarize a larger mass of the heart (16,19,20,21).

Efficacy of three sequential shocks. Three sequential shocks required less peak voltage than did two sequential shocks, but did not require less total energy. The reason for this may be that the total pulse duration of three shocks was longer than that of two shocks, and the reduction in peak voltage of the three shocks was not sufficient to offset the contribution of total pulse duration to total energy. It is possible that three sequential shocks of shorter duration would result in a reduction of the total energy required to defibrillate.

Defibrillation of infarcted versus normal hearts. The total energy required for defibrillation in dogs with myocardial infarction did not differ from that in the dogs without
infarction. This finding confirms those of previous studies (22,23). However, for pathways 1 + 2, the peak voltage to terminate ventricular fibrillation in normal hearts was significantly greater than that in hearts with infarction. The reason for this is unclear. One speculation is that the infarcted hearts received more shocks than did noninfarcted hearts, which might have resulted in a reduction in the resistance between electrodes and substantially reduced the defibrillation threshold (24,25). However, the peak voltage adjusted for body weight and body weight and number of shocks in dogs without infarction exceeded those of dogs with infarction; when the peak voltage was adjusted for number of shocks alone, there was no difference.

Defibrillation threshold and body weight. Peak voltage and total energy at defibrillation threshold were correlated with body weight of dogs with myocardial infarction, but not in dogs without infarction. The lack of correlation in the latter dogs was probably due to the small range in body weights and the large range in defibrillation thresholds. Our observations in the dogs with infarction confirm the findings of Tacker et al. in humans (26,27) and have been explained partly by a proportional increment in transthoracic resistance to body weight change (24,28). We found that this correlation existed not only for the current path between the right ventricular apical endocardial electrode of the catheter and the subcutaneous plate, but also for the current paths between intracardiac electrodes of the catheter alone and between the right ventricular apical endocardial electrode of the catheter and the epicardial patch. Recently, Chapman et al. (29) reported that defibrillation thresholds were significantly related to left ventricular mass calculated by two-dimensional echocardiograms. These findings further support previous studies from our laboratory (8) which showed that depolarizing a critical mass of myocardium was required to terminate ventricular fibrillation.

Peak voltage, peak current and total energy as the determinants of defibrillation efficacy. Whether these variables should be used to relate to defibrillation efficacy is not entirely clear. Total energy is a combination of voltage, current and pulse duration. It has been used most frequently to determine defibrillation efficacy (26,27) and to assess the extent of myocardial damage associated with defibrillation (30,31). The energy dose-weight concept introduced by Tacker et al. (27) has been recommended by the American Heart Association (32). However, subsequent studies (33–35) have shown no relation between energy required for defibrillation and the patient’s weight. Geddes et al. (26) proposed that peak current and, in particular, peak current per kilogram of body weight was a better measure of the requirement for clinical ventricular defibrillation than was delivered energy. In our study, the defibrillator output was designed to deliver a fixed peak voltage, and the peak current varied as the impedance changed. Our data showed that peak voltage \( r = 0.361, p = 0.0026 \) calculated peak current \( r = 0.279, p = 0.022 \) and total energy \( r = 0.447, p = 0.00015 \) were correlated with the body weight in Group I dogs (with infarction), and the difference in the correlation coefficient among these three variables was not significant (36). In Group II dogs (without infarction), the peak voltage, peak current and total energy at defibrillation threshold for single, two and three sequential shocks showed almost identical changes. Single shocks required greater peak voltage, peak current and total energy to defibrillate than did two and three sequential shocks. Therefore, peak voltage, peak current and total energy probably are all important variables in characterizing defibrillation efficacy.

Limitations. The present study is limited because data were obtained from anesthetized closed chest dogs, rather than from conscious animals. Second, defibrillation thresholds were determined at different times after electrode placement (immediately after placement of the catheter electrode and subcutaneous plate, 4 to 14 days after the epicardial patch was implanted in dogs with infarction, but immediately after implanting the epicardial patch in dogs without infarction). Defibrillation thresholds might change over time (37). Third, the location of the epicardial patch and subcutaneous plate was not adjusted to find the optimal site with the lowest defibrillation threshold. Fourth, there were some differences between Group I and Group II dogs (in the duration and tilt of waveform of shock because two different defibrillators were used, number of shocks and body weight of dogs), and the number of trials was small in some electrode combinations. Finally, we could have studied still more electrode combinations, and some might yield still lower defibrillation thresholds.

Clinical implications. We have shown that a single shock over a catheter electrode alone and over epicardial patches across the anterior and posterior left ventricle required greater defibrillation voltage and energy than did combinations using both the catheter electrode and epicardial patch or subcutaneous plate, or an epicardial patch-patch combination if the current pathway included the interventricular septum. When two sequential shocks were applied over the multiple lead system, both total energy and peak voltage were reduced significantly. Therefore, the size of the implantable cardioverter/defibrillator unit required and the risk of myocardial damage should be reduced by using the sequential shock mode. A dual lead system with a catheter electrode and subcutaneous plate seems to be preferable because a thoracotomy is not required. If the chest is to be entered, however, two sequential shocks over a three epicardial electrode system would be preferable, and surgery to implant the intracardiac lead becomes unnecessary. Three sequential shocks reduce the peak voltage but not the energy requirements compared with two sequential shocks.

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References


