Determinants of Intracardiac Current in Defibrillation

Experimental Studies in Dogs

ROBERT HOYT, B.S., JOSEPH GRAYZEL, M.D.,
AND RICHARD E. KERBER, M.D.

SUMMARY Defibrillation success depends upon the amount and distribution of intracardiac current (IC), because only a portion of total current flow between the paddles actually traverses the heart. We evaluated two determinants of IC: paddle size and shock energy. Studies were performed in 11 anesthetized dogs using a damped-sine wave form defibrillator. Intramyocardial electrode pairs were implanted subepicardially to subendocardially across the left and right ventricular free walls and in the interventricular septum. IC was quantitated by oscilloscopic measurements of the electric potential gradient (V/m) developed across the implanted electrodes during synchronized shocks of constant energy. External defibrillating paddle electrodes ("paddles") were applied to the left and right lateral chest walls. An initial group of six dogs was given shocks with 8.5-cm-diameter or 13-cm-diameter paddles to assess the effect of standard vs large paddles on IC. Mean IC values were substantially greater using 13-cm paddles (p < 0.01, paired t test). We then studied a second group of five dogs to determine more precisely the paddle size that produced the highest IC. A series of constant energy shocks using paddles of various sizes (8.5, 10, 12, 14, 16 cm in diameter) were given. In each dog, as paddle diameter increased from 8.5 cm to 16 cm, the IC increased, reached a maximum and then decreased. The maximum IC occurred at an average paddle size of 12 cm. To assess the effect of shock energy level on IC, we gave shocks of variable energy using 8.5-cm-diameter paddles. Each fourfold increase in delivered energy resulted in a doubling of IC. We conclude that defibrillating paddle diameter and delivered energy are important determinants of IC flow.

DEFIBRILLATION with an electrical pulse is the only clinically effective way to restore coordinated electromechanical activity to a fibrillating ventricle.1, 2 Although defibrillation is usually discussed in terms of delivered energy, it is the current flow traversing the heart that actually defibrillates.3 Successful defibrillation depends on developing sufficient intracardiac current density to depolarize more than a critical mass of excitable myocardial cells, terminating propagation of random fibrillatory excitations.4 For a constant duration electrical pulse of a given energy (J), the resistance (Ω) of the thorax in part determines the current (A) that flows between the paddles. The resistance of the thorax to current flow depends, to a large extent, upon the size of the defibrillating paddle electrodes ("paddles") used. Using very small paddles results in high transthoracic resistance,5 6 this implies a reduced total current flow that is unlikely to result in adequate current density in the heart to defibrillate unless the energy setting is very high. Relatively low transthoracic resistance is encountered using very large paddles; this results in an increased total current flow through the thorax, but does not necessarily yield maximal intracardiac current because with very large paddles a substantial amount of the total current may follow extracardiac pathways, ineffectively bypassing the heart.

The energy level in defibrillation identifies the amount of current traversing the thorax, but the relationship between energy level and intracardiac current density has not been previously reported.

In this study we evaluated the effects of various paddle sizes and energy levels on the magnitude and distribution of intracardiac current density. Our hypothesis was that in each subject there is an optimal paddle size to maximize intracardiac current from a shock of any given energy.

Methods

As defibrillation current flows through the thorax, an electric field or potential gradient is developed. For this study, we assumed that the conductivity of small areas of myocardium is constant and uniform over 1-2 hours. If so, the current density at any point in an electric field is proportional to the potential gradient measured over a small segment of tissue at that point.7 We assessed intracardiac current density during electric shocks by implanting electrodes in the ventricular myocardium and measuring the potential difference (V) developed across each electrode pair with shocks. The quotient of this potential difference and the distance separating the two electrodes was calculated to give the potential gradient in V/m.

Studies were performed on 11 adult, mongrel male dogs (mean body weight 24 ± 5 kg (±sd), range 17-30
kg). After anesthesia with i.v. chloralose-urethane, a cuffed endotracheal tube was placed and ventilation was maintained by a Harvard respirator. A midsternal thoracotomy was performed to implant the electrode pairs; the pericardium was incised and reflected to cradle the exposed heart. We chose representative sites for electrode implantation: the left ventricular free wall, the right ventricular free wall and the interventricular septum. An electrode bent to a "J" shape was hooked just beneath the epicardial surface of the left ventricular free wall. The second electrode of the pair was linear, and passed to a 6–10-mm depth directly below the surface electrode. Both were sutured in place. This arrangement allowed measurement of the potential gradient developed across the free wall in an epicardial-to-endocardial (epi/endo) direction (fig. 1). A similar epi/endo pair was placed in the right ventricular free wall. We located multiple electrodes in the interventricular septum at a site close to the transchest axis connecting the paddle centers. Voltage gradient through the heart in a lateral-lateral (S_L) direction was detected by passing two linear electrodes into the septum from either side of the left anterior descending coronary artery (the spacing between them was approximately 15 mm) to a depth of 15–20 mm below the epicardium. The left S_L electrode was paired with a "J" electrode hooked beneath the epicardial surface directly anterior to it, permitting measurement of potential gradients developed in the anterior-posterior (S_A) direction. An electrode passed 15–20 mm deep into the septum 15 mm caudal to the S_A site was paired with the left S_L electrode to detect potential gradients in the cephalo-caudal (S_C) direction. Electrodes in the septal region were also sutured in place. This array detected potential gradients along three mutually perpendicular or orthogonal vectors (fig. 1). At the conclusion of each study the heart was excised and sectioned to measure electrode separation. The electrode leads were brought out of the thorax through the midsternal incision; the chest was tightly reclosed with sutures drawn through the deep fascia.

Electrode Implants

Paired 0.33-mm-diameter stainless-steel bipolar electrodes were fabricated and insulated with an epoxy lamination, except for 1 mm exposed at the tip.

Defibrillator Paddles

A modifiedDatascope MD2J defibrillator, which delivers a 5-msec damped-sinusoidal pulse was used. For an initial group of six dogs, a pair of 8.5-cm-diameter (standard size) circular paddles or a pair of specially constructed 13.0-cm-diameter (large) paddles was compared. These sizes were selected because we have shown that the 13.0-cm-diameter paddles increase the total transthoracic current flow between the paddles in human defibrillation. A second group of five dogs was given shocks with a series of paddle pairs of 8.5, 10, 12, 14 or 16 cm in diameter. To create these progressively larger paddles, we used circular sheets of aluminum, 1 mm thick, cut to each specified diameter. Each pair of these circles was sewn to the chest wall. The 8.5-cm paddles were then pressed firmly against the equal or larger size aluminum circles and shocks delivered. This resulted in effective paddle-thoracic contact surfaces of 8.5, 10, 12, 14 and 16 cm in diameter. Care was taken to center the different size paddles over the same locations on the chest walls. Paddle placement was at the optimal sites reported by Geddes et al.: One paddle was positioned on the right hemithorax and one on the left, with the left paddle centered over the cardiac apex.

The chest was closely shaven. The paddle-thorax contact surfaces were coated with a uniform thickness of low-resistivity electrode paste (Redux, Hewlett-Packard). A spring-loaded paddle-holding apparatus ensured constant paddle position and paddle contact pressure.

Intracardiac Potential Gradients

Electrode potential differences were measured with a calibrated Tektronix triggered-sweep storage oscilloscope with a high input impedance (15 MΩ). Upon discharge of the defibrillator, the oscilloscope traced a damped-sine wave form. Voltage measurements were taken at the peak amplitude of this wave form. The distances separating the electrodes were measured upon subsequent sectioning of the heart, and these distances were used in the calculation of potential gradients.

Experimental Protocol

To measure the effect of varying paddle sizes on intracardiac current, in an initial group of six dogs, shocks using 8.5- or 13-cm-diameter paddles were administered in a random sequence with a constant delivered energy of 20 J throughout each study. Then, to assess the effect of a different variable, delivered energy, we administered shocks of different energies (5–100 J delivered energy, in random order) with a constant paddle size of 8.5 cm. To avoid possible
variations in intracardiac current due to respiratory movement, each shock was delivered at peak inspiration. The defibrillator pulse was synchronized to an ECG "R"-wave trigger, so intracardiac voltage measurements were taken at the same point of the cardiac cycle. Peak transthoracic current flow between the paddles (A) was also recorded for each shock from a display on the defibrillator control panel. At least 2 minutes elapsed between successive shocks.

In a second group of five dogs, the effect of increasing paddle sizes on transthoracic current and intracardiac potential gradients was assessed. The paddles of different sizes were applied to the chest in random order. A constant shock energy of 20 J was used. Again, all shocks were given on the "R" wave of the ECG, at peak inspiration.

Statistical Analysis

Analysis of paired data was performed using the t test to determine the significance of differences in intracardiac potential gradient developed during defibrillation with 8.5-cm-diameter vs 13-cm-diameter paddles. Intracardiac potential gradients measured at the orthogonal septal electrodes were compared by analysis of variance. For dogs given shocks with the graded series of paddle diameters, a plot of paddle size vs the mean intracardiac potential gradients of the left ventricle, right ventricle and Sx sites was drawn to determine the optimal paddle size for each dog. A companion plot of the transthoracic current flow at each of the graded paddle sizes was also drawn. Linear regression analysis was performed to correlate delivered energy with the magnitude of the intracardiac potential gradient.

Results

Effect of Paddle Size on Intracardiac Potential Gradient

Intracardiac potential gradients were significantly greater with large than with standard paddles at both the left and right ventricular free wall electrode implants (table 1). Potential gradients at the septal electrodes were also greater with large paddles, but the differences were not statistically significant (table 1). As previously noted, intracardiac current is proportional to the potential gradient, given the assumptions we made.

A measurement of intracardiac current in defibrillation that would represent an average current value taken from three widely separated areas in the heart was derived by calculating the average intracardiac potential gradient developed at the electrode implants located in the left and right ventricular free walls, and the Sx electrode pair in the septum. The Sx electrode was chosen from the three septal electrode pairs because its spatial orientation was similar to the right and left ventricular free wall electrodes. This average intracardiac potential gradient was 892 ± 433 V/m (± sd) with 13-cm-diameter paddles, compared with 715 ± 456 V/m with 8.5-cm-diameter paddles (p < 0.01).

In the second group of five dogs, as paddle diameter was increased from 8.5 to 16 cm, the transthoracic current flow between the paddles increased steadily (fig. 2), but the average intracardiac potential gradient in each dog first increased, reached a maximum in the middle range of paddle size, and then declined (fig. 3).

Relation of Intracardiac Potential Gradient to Delivered Energy

Using 8.5-cm paddles, intracardiac potential gradient was related to delivered energy (y = 0.26x + 0.96; r = 0.84, p < 0.01) (fig. 4). Intracardiac potential gradient was also related to transthoracic current flow (y = 0.94x + 0.13; r = 0.77, p < 0.01).

Effect of Electrode Orientation (Septum) on Intracardiac Potential Gradient

Using 8.5-cm or 13-cm paddles oriented laterally across the chest, intracardiac potential gradient was highest in the Sx electrode orientation (lateral-lateral direction) in four of the five dogs in which Sx data were obtained, and the mean Sx and Sy values differed significantly (table 1).

Discussion

The major findings of this experimental study are: (1) 13-cm-diameter defibrillating paddle electrodes result in greater intracardiac current flow than do 8.5-cm paddles; (2) intracardiac current is greatest at a specific paddle size in each dog, and this optimal size is approximately 12 cm in diameter for a 20-kg dog; (3) for two successive shocks, a fourfold increase in delivered energy is required to double intracardiac current; (4) defibrillation current may be resolved into directional vectors.

Ewy* showed that greater defibrillation success in dogs could be obtained with 12.8-cm-diameter paddles than with either 8-cm-diameter or 13 × 20-cm paddles. How can these findings be explained? Total transthoracic current flow between the paddles increases as paddle diameter increases, but this study provides the first demonstration that intracardiac current is maximum at a certain optimal paddle size. Beyond this optimal size, further increases apparently result in a substantial proportion of current traversing extracardiac chest pathways, reducing the intracardiac current available for defibrillation. With paddle sizes smaller than the optimal size, the amount of total transthoracic current flow is less, which also reduces the intracardiac current available. The optimal paddle size is variable (fig. 3); it was 10 cm for two 17-kg dogs, 12 cm for one 20-kg dog and 14 cm for a 22-kg and a 24-kg dog. Chest circumference measurements (available in four dogs) showed that the two dogs that had the smallest optimal paddle size (10 cm) also had the smallest chest circumferences. Although the number of experiments is small, these findings suggest that optimal paddle size probably becomes greater as body weight or chest circumference becomes larger.
TABLE 1. Effect of Paddle Size on Intracardiac Potential Gradient

<table>
<thead>
<tr>
<th>Paddle diameter (cm)</th>
<th>8.5</th>
<th>13</th>
<th>8.5</th>
<th>13</th>
<th>8.5</th>
<th>13</th>
<th>8.5</th>
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<td>± 5.2</td>
<td>± 553</td>
<td>± 557</td>
<td>± 395</td>
<td>± 366</td>
<td>± 394</td>
<td>± 556</td>
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<td>± 316</td>
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<td>&lt; 0.01</td>
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Abbreviations: LV = left ventricular; RV = right ventricular; S_x = lateral-lateral direction; S_y = cephalocaudal direction; S_z = anteroposterior direction.

The size and configuration of the dog's thorax differs significantly from those in man, and our results cannot be directly applied to humans. Therefore, this study does not establish the ideal size paddles for human defibrillation. However, adult human chests and hearts are considerably larger than those of the dogs we studied. Thus, 13-cm-diameter paddles are probably not too large for human hearts, and should result in increased intracardiac current in humans as well as in dogs. We have shown that 13-cm-diameter paddles increased total transthoracic current during human defibrillation compared with 8-cm paddles.

The finding of an optimal paddle size has important clinical implications. Some investigators have

**Figure 2.** Relation of paddle diameter to transchest current flow. With increasing paddle diameter, the transchest current flow between the paddles increased.

**Figure 3.** Relation of paddle diameter to intracardiac current flow. Each point represents average intracardiac potential gradient (E) obtained by averaging left and right ventricular and lateral-lateral electrode measurements. With increasing paddle diameter, E increased, reached a maximum and then decreased. In the two largest dogs (22 and 24 kg), highest E was achieved with 14-cm paddles; in the two smallest dogs (17 kg), highest E was achieved with 10-cm paddles.
suggested that presently available defibrillators could not provide current flow adequate to defibrillate very large patients, and have suggested that higher energy defibrillators should be manufactured. Others have vigorously disagreed. Larger (at least 13 cm in diameter) defibrillator paddles will probably result in increased intracardiac current flow at any given energy; this may improve defibrillation success with existing defibrillators.

A second consideration relates to shock-induced myocardial damage. Dahl et al showed that myocardial necrosis, assessed histologically and by electrocardiographic precordial mapping, was greatest after dogs were shocked with 4.3-cm-diameter paddles, intermediate with 8.0-cm-diameter paddles and least with 12.8-cm-diameter paddles. Although total transthoracic current flow is less with small paddles, such paddles may develop points of high current density in the myocardium that induce necrosis. Although the mean intracardiac current is increased with larger paddles, this current is distributed through a much larger cross-sectional area, so points of high current density and necrosis in the myocardium are less likely to occur. Thus, larger paddles may not improve defibrillation success, but may also reduce the amount of myocardial necrosis induced by repeated high-energy shocks.

Increasing the delivered energy with damped sinusoidal defibrillation pulses results in increased transthoracic current flow. However, the relationship of increasing delivered energy to intracardiac current has not been previously demonstrated. From basic physical considerations the power (rate of energy) delivered to a conducting medium equals I^2/R, where I is the current traversing the medium and R is its resistance. This square-law relationship predicts that doubling the current requires quadrupling the rate of energy delivered. If a fixed-duration sinusoidal pulse is used, this concept applies to the total delivered energy as well, which we measured. Our data are consistent with this basic law: With two successive shocks, if the energy of the second shock is four times that of the first, there is an approximate doubling of intracardiac potential gradient and thus of intracardiac current density (fig. 4). This probably explains the greater human defibrillation success at higher energies noted by Campbell et al, who evaluated the success rates of shocks given sequentially at 100, 200 and 400 J.

Finally, these studies show that the magnitude of the intracardiac potential gradient depends on the orientation of the measuring electrodes. Electrodes implanted in a lateral orientation across the septum showed higher potential gradients from lateral-lateral paddle shocks than did septal electrodes implanted in other orientations. Thus, defibrillation current has properties similar to an electric vector in a linear conducting medium.

Acknowledgment

We are grateful to Professor Robert Arzbaecher for his valuable advice and criticisms and to Donald Laughlin, MSEE, for expert technical assistance.

References

Effects of Quinidine on Atrioventricular Nodal Reentrant Paroxysmal Tachycardia

DELon Wu, M.D., JUI-SUNG Hung, M.D., Chi-Tai Kuo, M.D., KuNG-Shyu Hsu, M.D., AND wEn-Bin ShieH, M.D.

SUMMARY Electrophysiologic studies were performed in 14 patients with atrioventricular nodal reentrant paroxysmal tachycardia (PSVT) before and after oral administration of 1.2–1.6 g quinidine sulfate over a 24-hour period (0.3–0.4 g every 6 hours). Studies were performed after 0.5–1 mg i.v. atropine before and after quinidine. All 14 patients had induction of sustained PSVT before quinidine, with or without atropine. After quinidine, 11 patients lost the ability to induce echoes or sustain PSVT, reflecting depression of the retrograde pathway with either absence of atrial echoes (six patients) or induction of nonsustained PSVT, with termination of echoes or PSVT occurring after QRS (block in retrograde pathway) (five patients). In only one of these 11 patients was sustained PSVT inducible after addition of atropine. All 11 were discharged on the same dose of quinidine. In three patients, quinidine was discontinued because of side effects. Follow-up in the remaining eight patients for 8 ± 2 months showed no recurrence of sustained PSVT. Three of the 14 patients had induction of sustained PSVT after quinidine. Ventricular paced cycle length producing ventriculoatrial block was 314 ± 7 msec (mean ± SEM) before and 392 ± 13 msec after quinidine (p < 0.01) in the 14 patients, suggesting depression of the retrograde pathway with quinidine.

In summary, quinidine inhibited induction of sustained atrioventricular nodal reentrant tachycardia with depression of the retrograde pathway. It is very effective in preventing recurrence of PSVT in most patients.

DUAL PATHWAY atrioventricular (AV) nodal reentrant tachycardia, using a slow pathway for antegrade and a fast pathway for retrograde conduction, is a common arrhythmia.1, 2 Propranolol, digitalis and verapamil inhibit arrhythmias attacks by depression of antegrade slow pathway conduction.3–7 Procainamide inhibits arrhythmia attacks by depression of retrograde fast pathway conduction.8 Quinidine has also been recommended for treatment of paroxysmal supraventricular tachycardia (PSVT).9 Although data regarding the effects of quinidine on AV reentrant tachycardia are available,10–11 little information is available concerning the effects of quinidine on induction of AV nodal reentrant tachycardia.12, 13 We systematically examined the effects of oral quinidine sulfate and atropine on induction and maintenance of AV nodal reentrant tachycardia.

Methods

Criteria for inclusion in this study were (1) a history of electrocardiographically documented recurrent PSVT that required termination with i.v. medication; (2) electrophysiologic demonstration of AV nodal reentrant tachycardia using atrial and ventricular stimulatory techniques and mapping of atrial activation sequence during induced tachycardia;14, 2, 18–18 (3) electrical induction of sustained PSVT with all induced episodes of PSVT requiring electrical termination on the day of control study; and (4) electrophysiologic exclusion of AV reentrant tachycardia incorporating a retrogradely conducting anomalous pathway.16–20 Fourteen patients, two males and 12 females, ages 23–66 years (mean 44 ± 13 years [± SD]), were studied. All had a PSVT characterized by antegrade
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