Epicardial Mapping of Ventricular Defibrillation With Monophasic and Biphasic Shocks in Dogs

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To study the mechanism of defibrillation and the reason for the increased defibrillation efficacy of biphasic waveforms, the potential gradient in a 32×30-mm region of the right ventricle in 15 dogs was progressively lowered in four steps while a strong potential gradient field was maintained throughout the rest of the ventricular myocardium. The volume of right ventricle beneath the plaque was 10±2% of the total ventricular mass. A 10-msec monophasic (eight dogs) or 5/5-msec biphasic (seven dogs) truncated exponential shock 30% above the defibrillation threshold voltage was given via electrodes on the left ventricular apex and right atrium to create the strong potential gradient field. Simultaneously, a weaker shock with the same waveform but opposite polarity was given via mesh electrodes on either side of the small right ventricular region to cancel part of the potential difference in the region and to create one of the four levels of potential gradient fields. Shock potentials and activations were recorded from 117 epicardial electrodes in the small region, and in one dog global epicardial activations and potentials were recorded from a sock containing 72 electrodes. Each gradient field was tested 10 times for successful defibrillation after 10 seconds of electrically induced fibrillation. For both monophasic and biphasic shocks, the percentage of successful defibrillation attempts decreased (p<0.05) as the potential gradient decreased in the small region. Defibrillation was successful approximately 80% of the time for a mean±SD potential gradient of 5.4±0.8 V/cm for monophasic shocks and 2.7±0.3 V/cm for biphasic shocks (p<0.05). No postshock activation fronts arose from the small region for either waveform when the gradient was more than 5 V/cm. For both waveforms, the postshock activation fronts after the shocks were markedly different from those just before the shock and exhibited either a focal origin or unidirectional conduction. Thus, 1) for both monophasic and biphasic waveforms, defibrillation efficacy depends on the potential gradient fields; 2) a low potential gradient in approximately 10% of the ventricular mass can cause defibrillation to fail, suggesting that the critical mass for defibrillation is over 90% of the ventricular mass in dogs; 3) this low gradient field halts the activation fronts during fibrillation and then leads to new activation fronts to reinstate fibrillation; 4) postshock activation fronts are prevented by a potential gradient of more than 5 V/cm for both waveforms; and 5) the strength of the minimum potential gradient field required for defibrillation is less for the biphasic waveform. (*Circulation Research* 1993;72:145-160)

**KEY WORDS** • fibrillation • defibrillation • shock waveform • cardiac mapping • activation patterns

Although electrical ventricular defibrillation is performed hundreds of times daily, its mechanism is not definitely known. One hypothesized mechanism is that the activation fronts are halted within a critical mass of fibrillating myocardium.1,2 According to this mechanism, a shock fails to defibrillate because it is too weak to annihilate the activation fronts of fibrillation in this critical mass of myocardium. Recent mapping findings indicate that many of the activation fronts first observed after subthreshold defibrillation shocks appear to spread centrifugally from a discrete early site3-5 instead of spreading primarily in one direction, as would be expected if these activation fronts were the continuation of fronts present immediately before the shock. Another finding not explained by the above mechanism is the relatively long isoelectric window between the shock and the time of the earliest recorded activation after the shock.4,6 These and other findings led to the hypothesis that a shock slightly weaker than is necessary to defibrillate halts all of the activation fronts present during fibrillation, but after a latency period, the shock itself gives rise to new activation fronts that reinitiate fibrillation. However, the wide spacing between recording electrodes in these studies3-5 might have artificially caused the long postshock isoelectric windows, since small activation fronts could be present between electrodes during this interval.

Little is known about the strength of the potential gradient required for defibrillation by different shock waveforms.7,8 Several investigators have found that bi-
phasic waveforms, in which polarity is reversed during the shock, require less voltage and energy for defibrillation than do monophasic waveforms of the same, or half of the same, total duration in both animals and humans. The mechanism of this increased efficacy of biphasic waveforms is not known.

The development of computer-assisted cardiac mapping systems has made it possible to determine the potential gradient field generated by a shock and to evaluate how the myocardium responds to this field. The purpose of the present study was to obtain this information in dogs for representative monophasic and biphasic waveforms by 1) studying the effect of the shock potential gradient field on the efficacy of the defibrillation shock, 2) examining the relation between preshock and postshock activation patterns, 3) determining the potential gradient at which the activation fronts of fibrillation are halted, and 4) estimating a lower limit for the size of the critical mass for defibrillation. These goals were accomplished by creating a strong potential gradient field throughout much of the ventricular myocardium while a lower potential gradient field was created in a 32×30-mm region of the right ventricle, in which 117 mapping electrodes were concentrated.

Materials and Methods

Recording Electrodes

An electrode array was sutured directly to the epicardium of the right ventricle, and recordings were made simultaneously from 117 electrodes over a 32×30-mm area of epicardium (Figure 1). The electrodes were within a plaque 4 cm long and 3.2 cm wide. There were nine rows and 13 columns of bipolar electrode pairs in the plaque. Cardiac activations were recorded with the bipolar electrodes. Unipolar recordings from one contact of each bipolar pair were made to record the potentials generated by the defibrillation shocks. These potentials were measured with respect to the dog’s left hind leg.

In one of the animals in which the monophasic waveform was tested, an elastic sock containing 72 bipolar button electrodes was used to record epicardial activations and shock potentials over the remainder of the ventricles not covered by the plaque electrodes (Figure 1). Each pole of the bipolar button electrodes was 1 mm in diameter, and the poles were separated by 2 mm from center to center. In this same animal, atrial activations were recorded from six epicardial loop electrodes sutured to the atria.

Surgical Preparation

Fifteen mongrel dogs, eight in which the monophasic waveform was tested (mean±SD, 25.7±1.4 kg) and seven in which the biphasic waveform was tested (26.4±2.1 kg), were anesthetized with pentobarbital (30–35 mg/kg) and succinylcholine (1 mg/kg). Each was intubated with a cuffed endotracheal tube and ventilated with 30–60% oxygen through a Harvard respirator (Harvard Apparatus, South Natick, Mass.). Body temperature was continuously monitored and maintained at 36–38°C. Ringer’s lactate was continuously infused and supplemented with potassium chloride, sodium bicarbonate, and calcium chloride when needed. Pentobarbital was infused through a separate intravenous line at a rate of approximately 1 mg/min throughout the experiment to maintain adequate anesthesia. This dose of pentobarbital was adjusted according to the depth of anesthesia, which was assessed by signs such as shivering, eyelid reflexes, and pedal reflexes. A 10-mg bolus of succinylcholine was given intermittently to control muscle contraction induced by the electric shocks. An arterial line was inserted through the femoral artery, and the systemic blood pressure and surface electrocardiogram were continuously displayed on an oscilloscope. Blood samples were taken every 40 minutes to determine the pH, Po2, and Pco2 and bicarbonate, sodium, potassium, and calcium concentration. Normal metabolic status was maintained throughout the experiment by correcting any abnormal value.
The chest was opened through a median sternotomy, and the heart was suspended in a pericardial cradle. The plaque containing 117 epicardial recording electrodes was applied to the epicardial surface of the right ventricle. Round defibrillation electrodes (25 mm in diameter) were sutured to the right atrium as the anode for monophasic and the first phase of biphasic shocks and to the left ventricular apex as the cathode (Figure 1A). A test shock from a defibrillator (model HVS-02, Ventritex, Sunnyvale, Calif.) was delivered through the defibrillation electrodes, and the defibrillation electrodes were moved until the potential field produced by this test shock was fairly uniform within the area containing the plaque electrodes. Two mesh electrodes (5 × 40 mm) were sutured approximately 0.5–1 cm to either side of the plaque (Figure 1A). Shocks were administered through these two inner electrodes from a second HVS-02 Ventritex defibrillator, with the electrode closer to the left ventricle as the anode for monophasic and the first phase of biphasic shocks and the electrode closer to the right atrium as the cathode. These two inner electrodes were parallel to each other and perpendicular to the field created by the outer pair of defibrillation electrodes. Thus, the electric field beneath the plaque generated by shocks through this inner pair of electrodes was antiparallel to the field generated by the outer pair of electrodes. By changing the strengths of the shocks and giving shocks simultaneously through the two sets of electrodes from the two defibrillators, different degrees of cancellation of the electric field could be created in the region beneath the plaque of recording electrodes. No attempt was made to add resistance to one of the pairs of electrodes to match the impedances for the two pairs of electrodes, because pilot studies indicated that both impedances were similar (approximately 100 Ω).

**Data Acquisition**

Simultaneous recordings were made from the 117 epicardial plaque electrodes with a 128-channel computer-assisted cardiac mapping system. In one animal, the 72 sock electrodes and six atrial electrodes were also recorded with a second 128-channel mapping system similar to and synchronized with the first. For recording activations, each amplifier could record signals to ±500 mV in either the unipolar or bipolar mode. An attenuator circuit was rapidly switched in front of each amplifier to record shock potentials of up to ±500 V in the unipolar mode. Both the attenuator and the unipolar/bipolar settings were controlled by a microprocessor.\(^{16,20}\)

The sequence of events that occurred when shock potentials were recorded was as follows: Bipolar electrograms for determining cardiac excitation were recorded with the amplifiers AC-coupled with a 5-Hz high-pass filter. Approximately 10 msec before the beginning of the shock, an external timing device signaled the mapping system microprocessor that a shock was imminent. The microprocessor switched the attenuators in place, changed the mode of recording to unipolar (referred to the left leg), changed the amplifier coupling to DC, and modified the gain of each channel to a preset value appropriate for the particular shock that was to be given. The relays took approximately 5 msec to switch and settle, whereas the gain and coupling changes occurred within 1 msec. For the remainder of the period before the shock, a baseline was established to which the shock potential on each channel was referenced. At the end of the shock, the external timing device signaled the mapping system to return to the initial conditions. The attenuators were switched out, and the gains and coupling were returned to their preshock values. Approximately 4 msec after the shock, the relays were reconnected to the recording electrodes. The signals were recorded digitally at a rate of 1,000 samples per second per channel, together with the real time information indicating the sequence of events during recording,\(^{21}\) and were stored on a videotape for off-line analysis.\(^{22}\)

**Defibrillation Protocol**

The defibrillation threshold (DFT) was determined as follows: Ventricular fibrillation was induced by 60-Hz AC delivered through two stainless-steel wires on the anterior wall of the left ventricle. After fibrillation was sustained for 10 seconds, defibrillation was attempted by applying 10-msec monophasic (in eight dogs) or 5/5-msec biphasic (in the other seven dogs) truncated exponential shocks through the outer defibrillation electrodes described above. When the biphasic waveform was used, the leading voltage of the second phase was set equal to the trailing voltage of the first phase with opposite polarity to make it similar to the output of a defibrillator with a single capacitor (Figure 1D). The DFT was determined by a method similar to that described by Bourland et al.\(^{23}\) The first shock was given with a predicted voltage of 300–350 V. If defibrillation was successful, the strength of the next shock was decreased by 20 V. Subsequent shocks were decreased in decrements of 20 V until a defibrillation attempt failed. The strength of the shock was then increased by 10 V, and the lowest shock that achieved defibrillation was considered as the DFT. If the initial test shock failed to defibrillate, a salvage shock, with the same waveform as the test shock and a strength approximately 50% higher than the mean DFT for the previously studied dogs, was given within 30 seconds of the onset of ventricular fibrillation through the outer defibrillation electrodes. There was a 5-minute interval before the next fibrillation episode. Subsequent test shocks were then increased in increments of 20 V until defibrillation was achieved. The shock strength was then decreased by 10 V, and the lowest voltage that successfully defibrillated was designated as the DFT.

After the defibrillation threshold was obtained, a shock voltage 30% above the DFT was delivered through the outer defibrillation electrodes from one defibrillator while simultaneously a weaker shock was delivered through the inner mesh electrodes from the second defibrillator. The strength of the shock delivered through the second defibrillator was adjusted until the potential gradient field within the small mapped area approximately canceled the field created by the outside defibrillation electrodes, thus creating a gradient field as low as possible throughout the small mapped area (G1). The output of the second defibrillator was then adjusted to create potential gradients through the mapped area of two intermediate levels in addition to the lowest gradient field (G2 and G3). A fourth level, the highest gradient field, was created by not giving a shock through the second defibrillator, so that the shock field gener-
ated by the first defibrillator was unopposed (G4). The four levels of potential gradient fields were made as similar as possible in different dogs. The four levels of potential gradient fields were tested 10 times each for defibrillation with either monophasic or biphasic shocks in each dog after 10 seconds of electrically induced ventricular fibrillation. Voltage, current, impedance, and energy of the delivered shocks were measured by a waveform analyzer (model DATA 6000, Data Precision, Danvers, Mass.).

**Histological Studies**

The heart was fibrillated electrically to kill the dog, and the heart was excised. After the whole ventricles were weighed, the tissue beneath the plaque and mesh electrodes was cut out and weighed separately. The tissue was then fixed in 10% formalin for at least 48 hours. Serial sections of the mapped tissue were obtained every 0.5 mm parallel to the epicardial surface and stained with hematoxylin and eosin. Epicardial fiber orientation was determined with respect to the horizontal axis of the plaque.

**Data Analysis**

The percentage of successful defibrillation attempts for 10 episodes at each level of potential gradient field was determined. To analyze the potentials recorded during the shock, the tracing from one electrode was displayed on a computer workstation (model 3/50, Sun Microsystems). Based on known calibration signals, the potential recorded by each electrode 5 msec after the beginning of the shock was calculated by a computer program. For the typical impedance observed in this study, this potential is approximately 72% of the peak voltage at the leading edge of the shock and is approximately equal to the mean voltage of the shock. The potential gradient in volts per centimeter was calculated from the potential differences and the interelectrode distances between each recording electrode and its neighbor by a finite element method described in the appendix of a previous publication. Since neighboring electrodes were not present on all sides of the electrodes at the edge of the plaque or the sock, potential gradients were not calculated for these sites.

The recordings from each channel were displayed on the computer workstation for selection of activation times. The time of activation was taken as the time of the fastest slope for biphasic activation complexes and the time of the absolute peak magnitude for monophasic and triphasic activation complexes. Three activations immediately before and three immediately after the shock were identified. Isochronal maps were drawn for all six activations. Regions in which conduction velocity would have been less than 0.09 m/sec if conduction had been present were designated as exhibiting conduction block and indicated on the isochronal maps by block lines. The early activation sites, defined as sites that were activated earlier than all surrounding electrode sites beneath the plaque, were determined from the isochronal map of the first activation after the shock. The interval between the beginning of the shock and the first postshock activation detected at the early site was called the isoelectric window width. The pre-shock interval was defined as the interval between the last pre-shock activation at the electrode site registering earliest activation after the shock and the beginning of the shock. The preshock cycle length was the interval between the second from last and the last activations just before the shock at the postshock early site, i.e., the basal cycle length during ventricular fibrillation. Data were analyzed using paired or unpaired Student’s t test, analysis of variance, and the χ² test. Values of p<0.05 were considered significant. Values are given as mean±SD.

**Results**

**Potential Distribution and Potential Gradient Field Generated by Two Opposing Shocks**

The DFT of the biphasic waveform was 293±36 V, which was significantly lower than that of the monophasic waveform at 337±24 V (p<0.05). The defibrillation shock voltage through the outer defibrillation electrodes was increased to 30% greater than the DFT. To cancel the field created by this defibrillation shock beneath the plaque, a weak shock was simultaneously applied through the inner mesh electrodes. The weak shocks were 65.4±7.5, 43.4±7.6, and 19.7±4.8 V for the biphasic waveform and 78.8±12.8, 55.0±7.5, and 23.0±12.1 V for the monophasic waveform to create three successively higher potential gradient fields.

The four levels of mean potential gradient fields beneath the plaque were 1.8±0.2, 2.7±0.3, 4.9±0.4, and 10.9±0.8 V/cm for the biphasic waveform and 1.9±0.3, 2.9±0.5, 5.4±0.8, and 12.9±1.7 V/cm for the monophasic waveform. These values were obtained by averaging the potential gradients at the 77 recording sites that were not at the periphery of the plaque. There were no significant differences between the low potential gradient fields created by the biphasic shocks and by the monophasic shocks beneath the plaque. The highest gradient field created by the biphasic shock is lower than that created by the monophasic shock (p<0.05), because the DFT of the biphasic shock is lower than that of the monophasic shock. The magnitudes of the potential gradient fields calculated from the potential fields are shown for one animal in Figure 2. The four levels of potential gradient fields beneath the plaque are quite different, although there are only small differences in the potential gradient field outside the plaque. Except for sites near the plaque, the potential gradient at most of the sock electrodes was more than 5 V/cm. The potential gradient fields are characterized by isogradient lines that are approximately circles perpendicular to and centered around the long axis of the heart. The potential gradient was greatest at the apical portion of the ventricles near the ventricular defibrillation electrode. Hence, the epicardial gradient was smaller in the basal half of the ventricles than in the apical half.

**Potential Gradient Field and Percentage of Success of Defibrillation**

The percentage of success of defibrillation for either the monophasic or biphasic waveform decreased with the decrement of the potential gradient field in the plaque area. Figure 3 illustrates that the lower gradient fields have a smaller probability of success than the higher gradient fields and that the efficacy of the defibrillation shock is strongly influenced by the low potential gradient fields in the small plaque area. In addition, the percentage of success of defibrillation was
FIGURE 2. Examples of four levels of potential gradient fields created by cancellation of opposing shocks in one animal. Panels A–D represent the four levels of potential gradient fields created by the four shock combinations: a 386-V shock through the outer electrodes plus a simultaneous shock of 0 V (panel A), 17 V (panel B), 45 V (panel C), and 63 V (panel D) via the inner electrodes. The potential fields are shown beneath the plaque (maps on left side of figure) and over the entire ventricular epicardium (numbers on right side of figure). Numbers represent the locations of the recording electrodes and give the potential gradients (in volts per centimeter) that were calculated from the recorded potentials. Dots indicate electrode sites for which no gradient was calculated because they lacked neighboring electrodes on all four sides. The isogradient lines are 20 V/cm apart. Higher potential gradients are near the apex, and lower gradients are at the base. The mean values of the four potential gradient fields beneath the plaque are shown in the dashed-line area, which represents the plaque location, and are 12.0, 4.1, 2.5, and 1.6 V/cm for panels A–D, respectively. This and all later maps with sock electrodes are taken from the same animal.
Figure 3. Bar graph showing the relation between gradient field and percentage of success of defibrillation. On the ordinate is the mean percentage of success rate for 10 defibrillation episodes for all animals at each level of potential gradient. On the abscissa are the four levels of mean gradient fields created by the four shock combinations, with G1 representing the weakest field and G4 representing the strongest. The percentage of success of defibrillation was higher for biphasic than for monophasic waveforms when the lowest potential gradient fields (1.8–2.7 V/cm) were created in the mapped region. An asterisk indicates a significant difference (p<0.05) for monophasic vs. biphasic waveforms for that potential gradient field. The top horizontal line indicates a significant difference (p<0.05) for the percentage of success for the lowest potential gradient field vs. the percentage of success for the other three levels of potential gradient fields for both monophasic and biphasic waveforms. The lower horizontal line indicates a significant difference (p<0.05) for the percentage of success at one potential gradient field level (G2) vs. the percentage of success at the higher two levels of potential gradient fields (G3 and G4) for the monophasic waveform.

Postshock Isoelectric Window Width After Successful Shock Episodes

Successful defibrillation episodes have been classified into two types, called type A and type B. Type A defibrillation is characterized by a relatively long postshock isoelectric window width (more than 130 msec), whereas type B is characterized by a relatively short postshock isoelectric window (less than 130 msec). Except for the one experiment in which global sock recordings were made, it was not possible to determine the true isoelectric window, since the site of the earliest postshock activation may have been outside the small region beneath the plaque. However, successful defibrillation episodes with both long and short isoelectric windows in the tissue beneath the plaque were observed in this study.

An example of a successful defibrillation episode with a long isoelectric window is shown in Figure 4. Panels A–C illustrate the maps of the last three cycles of fibrillation just before the shock, which created a mean potential gradient field of 12.0 V/cm beneath the plaque. Activation during fibrillation was too complex to be adequately mapped with the wide electrode spacing in the sock; therefore, the sock activation maps before the shock are not shown. Under the plaque, activation fronts formed a reentry pattern that was fairly repeatable for all three cycles. The shock was delivered at 309 msec. The hatched area in panel C had not yet been activated for this cycle of ventricular fibrillation when the shock was given, as indicated by the fact that no activations were recorded in this area. Panels D–F of Figure 4 show the first three cycles after the shock. The activation fronts of fibrillation appear to have been halted by the shock, since the activation pattern differed markedly from that before the shock. No early sites for the first postshock cycle were recorded in the plaque area (panel D1). The earliest postshock activation (arrow) was recorded outside the plaque, 214 msec after the beginning of the shock (panel D2). Activation patterns were more organized after the shock and could be followed from the sock recordings. The second and the third cycles arose from the same location as the first postshock cycle with a regular rhythm (panels E and F). Atrial activation following the defibrillation shock appeared later than ventricular activation, which suggests that the early sites for activation could be arising from the ventricular myocardium or the specialized conduction system.

An example of a successful defibrillation episode with a short isoelectric window is illustrated in Figure 5. Three activation maps are shown both before and after a shock that created a mean potential gradient field of 2.5 V/cm beneath the plaque. Before the shock (panels A–C), there was one early site beneath the plaque, and reentry was present. All three cycles were similar. The shock was given at an activation time of 385 msec. The activation sequences following the shock differed markedly from those just before the shock. In the map of the first postshock cycle, two early sites were recorded in the plaque area, both appearing 63 msec after the beginning of the shock (panel D1). Activation fronts propagated away from the plaque area to activate the remainder of the ventricles (panel D2). Reentry was not observed in the plaque maps, although conduction block was present. The activation sequence just before the shock (panel C) suggests that the myocardium in the central portion of the plaque may have been directly excited by the shock, since these cells were most recovered when the shock was given. This would explain why the activation fronts from the early sites did not immediately propagate into this central area. About 130 msec later, the second cycle appeared, also from two early sites in
the plaque area, and propagated in a pattern similar to the previous cycle (panels E1 and E2). After these two rapid cycles, early sites for subsequent cycles arose from the same location as for the example of type A defibrillation shown in Figure 4D for this animal and gave rise to large, organized activation fronts (Figure 5F). Thus, after two rapid activations arising from the plaque area, the rhythm became regular.

In most cases the duration of the postshock isoelectric window appeared related to the potential gradient of the shock beneath the plaque (Table 1). The postshock isoelectric window usually increased with an increase in

**Figure 4.** A successful monophasic defibrillation shock followed by a long isoelectric window. A 386-V shock was given through the outer electrodes, and no shock was delivered through the inner electrodes, which created a mean gradient field of 12.0 V/cm beneath the plaque. Isochronal maps from the plaque electrodes are shown in panels A, B, and C for the last three consecutive activations before the shock and in panels D1, E1, and F1 for the first three activations after the shock. Isochronal maps from the sock electrodes are shown for the first three activations following the shock in panels D2, E2, and F2. Numbers represent the times of activations at the recording electrode sites. Time zero is taken as the earliest activation in panel A. The numbers in panels D, E, and F represent the times of activations after the beginning of the shock. The isochronal lines are 20 msec apart. Arrows indicate the early sites for each cycle. Dots indicate electrode sites where excitation complexes are missing because of inadequate recordings. Black bars represent regions of conduction block, and striped bars represent frame lines, which indicate the portions of the reentrant pathways that serve as the dividing line between successive isochronal maps. Frame lines are necessary to represent the continuous process of reentry by a series of static maps. The hatched area in panel C has not yet been excited by the activation fronts for this cycle of fibrillation when the shock is given. The general direction of myocardial fiber orientation is parallel to the double-headed arrow above panel A. During the three fibrillation cycles, reentry occurs repeatedly beneath the left center of the plaque. The fibrillation activation fronts are halted by the shock, and only one early site outside the plaque is recorded 214 msec after the shock (panel D2).
the potential gradient field ($p<0.05$ for responses after monophasic shocks).

Activation Patterns After the Defibrillation Shocks
The activation patterns following successful and unsuccessful defibrillation episodes for both monophasic and biphasic waveforms could be divided into two patterns. One pattern was characterized by the formation of unidirectional conduction. Some episodes with this activation pattern suggested reentry as shown in Figure 6 for an unsuccessful shock episode. Panels A–C show the maps of the last three cycles just before a monophasic shock that created a mean potential gradient field of 2.5 V/cm beneath the plaque and failed to defibrillate. Before the shock, the activation fronts invaded the mapped tissue beneath the plaque from the periphery, as indicated by the arrows. Most portions of the plaque area were activated by the fronts passing repeatedly from right to left. These fronts overlapped in time; the front for cycle B entered the tissue beneath the plaque at 135 msec, 14 msec before the front for cycle A had activated the lower left corner of the tissue at 149 msec. The shock was given at 344 msec. The hatched area in panel C had not yet been activated at the time of the shock, because no activations were recorded just before the shock for this cycle. The activation sequences after the shock differed from those immediately before the shock. The earliest postshock

**Figure 5.** A successful monophasic shock followed by a short isoelectric window. A 386-V shock was given through the outer electrodes, and a shock of 45-V was delivered through the inner electrodes, which created a mean gradient field of 2.5 V/cm beneath the plaque. Isochronal maps from the plaque electrodes are shown in panels A, B, and C for the last three consecutive activations before the shock and in panels D1, E1, and F1 for the first three activations after the shock. Isochronal maps from the sock electrodes are shown for the first three activations following the shock in panels D2, E2, and F2. Before the shock (panels A–C), a reentry circuit was formed beneath the plaque. After the shock, two early sites were recorded beneath the plaque and spread away, activating all of the ventricles in panels D and E. In the third postshock activation map (panel F) only one early site was recorded, which was outside the plaque area. For explanation of maps, see Figure 4 legend.
activation was recorded beneath the center of the plaque 54 msec after the beginning of the shock (panel D1), and the activation front was only able to conduct toward the top, right, and bottom. The activation front conducted unidirectionally away from the frame line (the striped line) and spread slowly counterclockwise so that the area that was activated earliest after the shock would have enough time to recover so that it could be reexcited when it was reached by the propagating activation front, allowing a leading circle type of reentrant pathway to form.28 In other episodes of failed defibrillation, activation patterns characteristic of figure-of-eight reentry29 were also observed. The time required to complete the first reentry loop, which equaled the time between the first and the second postshock activation at the early site, was 81 msec. From there the next cycle began and spread similarly (panels E and F). The second (panel E) and the third (panel F) reentry cycles took 130 and 136 msec, respectively, which was longer than for the first reentry loop. In this episode, no postshock early sites were recorded outside the plaque area in the maps of the first three cycles (panels D2, E2, and F2). Activations adjacent to the plaque were recorded later than those inside the plaque area, suggesting that the myocardium outside the plaque was activated by the activation front originating from the early site beneath the plaque.

The pattern of unidirectional activation was also observed after biphasic shocks. Figure 7 shows the unidirectional activation pattern following an unsuccessful biphasic shock, which created the lowest of the four potential gradient fields beneath the plaque (1.8 V/cm). Panels A–C show the last three activations during fibrillation before the shock. Most of the mapped tissue was excited by the activation front entering from the right side (arrow) of the plaque; another early site (arrow) appeared in the plaque area 25 msec later (panel A). Similar activation fronts repeatedly propagated from cycle to cycle (panels B and C). The shock occurred at 286 msec. The activation sequences after the shock differed from those immediately before the shock. The earliest activation (arrow) is recorded 31 msec after the beginning of the shock (panel D). The activation front originating from the early site conducted unidirectionally upward and to the left. The activation front then circled counterclockwise to reenter the tissue where the first early postshock site occurred. The second (panel E) and the third (panel F) cycles were propagated similar to the first.

The other kind of activation pattern was focal, in which the activation front appeared to spread centrifugally from an early site. This pattern was also observed after both monophasic and biphasic shocks. In the example shown in Figure 8, a monophasic waveform was used, and the shock was unsuccessful. The preshock activations (panels A–C) during ventricular fibrillation again were fairly similar from cycle to cycle. One early site (arrow) was recorded beneath the plaque, and activation fronts also invaded the tissue from outside the left side of the plaque. The shock, which created a mean potential gradient field of 1.6 V/cm beneath the plaque, was given at 303 msec. An early activation was recorded beneath the plaque 58 msec after the shock, and an activation front spread centrifugally from the early site in a focal pattern (panel D1). This early site arose from almost the same location in the maps of the second and third postshock cycles, with cycle lengths of 109 and 123 msec, respectively (panels E1 and F1). A second early site was probably superior to the plaque area for the first three postshock cycles also (panels D2, E2, and F2). The remainder of the ventricles appeared to be excited by activation fronts arising in or near the plaque region. Regions of block were formed both inside and outside the plaque area.

### Potential Gradients and Early Postshock Activation Sites

Numerous sites of early postshock activation were observed beneath the plaque with the lowest gradient field, but as the potential gradient field beneath the plaque was increased, fewer early sites were recorded, and no early sites were observed beneath the plaque when the highest potential gradient field was created (Table 2). The potential gradient at early activation sites after unsuccessful defibrillation episodes was always less than 5 V/cm. At the lowest and the second lowest potential gradient fields (G1 and G2), fewer postshock early activation sites were induced after biphasic shocks than after monophasic shocks. Seventy-nine percent of monophasic G2 episodes with early sites of postshock activation were unsuccessful, whereas only 31% of biphasic G2 episodes with early sites of postshock activation were unsuccessful ($p<0.05$, Table 2). More unidirectional activation patterns were observed than focal activation patterns for the two lower levels of the potential gradient fields. There was no significant difference in the relative incidence of activation patterns for monophasic and biphasic waveforms. In some cases, more than one early site or both focal and unidirectional conduction patterns were observed beneath the plaque after the same shock. Thus, the sum of the number of episodes of foci and of unidirectional conduction was larger than the number of episodes with early sites in the mapped region.

### Postshock and Preshock Interval at Early Sites

Immediately after the resumption of recording after the shock, an interval occurred during which no epicardial activation was recorded by any plaque electrode,

### Table 1. Width of Postshock Isoelectric Intervals

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<tr>
<th>Responses after the shock</th>
<th>Isoelectric window width (msec)</th>
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<tr>
<td><strong>Unsuccessful DF</strong></td>
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<tr>
<td>Monophasic</td>
<td>56±12*</td>
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<tr>
<td>Biphasic</td>
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</tr>
<tr>
<td>Successful DF</td>
<td></td>
</tr>
<tr>
<td>Monophasic</td>
<td>56±14*</td>
</tr>
<tr>
<td>Biphasic</td>
<td>40±7</td>
</tr>
<tr>
<td>All DF episodes</td>
<td></td>
</tr>
<tr>
<td>Monophasic</td>
<td>56±12*</td>
</tr>
<tr>
<td>Biphasic</td>
<td>43±18</td>
</tr>
</tbody>
</table>

G1–3, the three lowest potential gradient fields in ascending order; DF, defibrillation. Values are mean±SD.

No early activation sites were present beneath the plaque after the highest gradient shocks (G4).

*p<0.05 vs. biphasic shock.
i.e., the postshock interval. The earliest postshock activations arose from one of the outer rows of the plaque for most successful defibrillation episodes and for some unsuccessful defibrillation episodes. Thus, in these cases we do not know the true postshock interval (the isoelectric window width), because the site of earliest postshock activation probably was outside the plaque. For all defibrillation episodes with early postshock activations beneath the plaque, the postshock interval was significantly shorter for biphasic than for monophasic waveforms (Table 3). The mean preshock interval at the early postshock activation sites for these same episodes was significantly longer for the biphasic than for the monophasic waveform (Table 3). The last full cycle length during ventricular fibrillation just before the shock at the sites of the earliest postshock activation was 101±14 msec for monophasic and 96±11 msec for biphasic waveforms (p=NS). These intervals imply that the shock was delivered at a time when the cells at the early postshock activation sites had recovered to 66±15% of their cycle length for the biphasic waveform (63 msec/96 msec) and 56±19% for the monophasic waveform (56 msec/101 msec, p<0.01 for biphasic versus monophasic waveforms). Thus, myocardium at the early postshock activation sites was at an earlier stage in the cardiac cycle at the time of the shock for monophasic than for biphasic waveforms.

**Impedance of Monophasic and Biphasic Shocks**

The mean impedance at the DFT with the monophasic shocks (100±11 Ω) was lower than that with the biphasic shocks (111±11 Ω, p<0.05). For the biphasic...
waveform, the impedance of the first phase (111±11 Ω) was higher than that of the second phase (106±10 Ω, \( p<0.05 \) versus the first phase).

**Ventricular Myocardial Weight**

The ventricular weight was 171±35 g for hearts receiving monophasic shocks and 179±19 g for those receiving biphasic shocks (\( p=NS \)). The mass of the right ventricular muscle beneath the plaque and the inner mesh shocking electrodes was 16±4 g for monophasic shocks and 17±2 g for biphasic shocks (\( p=NS \)). Thus, the percentage of ventricular mass exposed to the low potential gradient field was approximately 9±3% for monophasic shocks and 10±1% for biphasic shocks (\( p=NS \)).

**Discussion**

**Importance of Potential Gradient for Defibrillation**

This study tests the hypothesis that the shock potential gradient in a small region of the heart is an important factor influencing the success or failure of defibrillation. In the few reports that suggest the possible importance of the potential gradient for defibrillation,7,8,25 the potential gradient changed gradually over a large distance; therefore, its precise relation with defibrillation outcome was not definitely known. Also, some theoretical studies predict that there should be no relation between the extracellular potential gradient and the success or failure of defibrillation.30

We tested this hypothesis by maintaining a high potential gradient throughout most of the ventricular...
myocardium except for one small region, where the gradient was set to either high, intermediate, or low values. The potential gradient field in this region was controlled by giving a second smaller shock simultaneously and opposite in orientation to the primary defibrillation shock, to cancel part of the field. As shown in Figure 2, this maneuver created different levels of potential gradients in the region without significantly perturbing the potential gradient distribution throughout the remainder of the ventricles except near the two inner mesh defibrillation electrodes on either side of the region.

Our results confirm the hypothesis. The outcome of defibrillation was strongly and directly related to the value of the potential gradient within the small region. For both monophasic and biphasic waveforms, the success rate for defibrillation increased as the potential gradient was increased within the small region (Figure 3). Activation fronts arose in the small region of low potential gradient from which they spread to capture the remainder of the ventricles (Figures 5, 6, and 8).

This study also shows that, if the extracellular potential gradient is less than a certain minimum value in approximately 10% of the ventricular mass, defibrillation is likely to fail. It remains to be determined if a minimum potential gradient is required in even a smaller volume of myocardium to ensure successful defibrillation. Thus, the critical mass for defibrillation in dogs is 90% or more of the total ventricular mass. The evidence in support of this conclusion has at least three limitations: 1) The low gradient region was produced only in the right ventricular outflow tract; mass requirements for defibrillation may be different in other parts of the ventricles. 2) The gradients may have been lower...
near the endocardium than on the epicardium; this possibility was increased by the fact that the epicardial boundary was adjacent to an insulator, air, that would increase gradients near the epicardium. 3) Low gradients may have been produced also in the portion of the ventricular septum beneath the right ventricular outflow tract; however, this may have been offset by inclusion of the high gradient regions beneath the two inner mesh electrodes that we included within the mass of the low gradient region. If the conclusion is true, the safest course in designing electrode configurations for defibrillation is to develop configurations that exceed a minimum potential gradient throughout all, or almost all, of the myocardium.

**Mechanism of Early Postshock Activation**

Early postshock activation may be hypothesized to have arisen beneath the plaque by at least four different mechanisms: 1) The unaltered propagation hypothesis postulates that the shock potential gradient field could have been too weak to affect the tissue beneath the plaque; therefore, activation fronts beneath the plaque at the time of the shock continued unaltered after the shock. Thus, activation fronts after the shock should arise by propagation from the fronts present at the time of the shock, and the pathways of these fronts should be unaltered by the shock. 2) The altered propagation hypothesis postulates that the shock potential gradient field could have been strong enough to affect conduction velocity and refractoriness but not strong enough to directly excite tissue beneath the plaque so that the pathways of activation fronts were altered by the shock. Thus, activation fronts after the shock should arise by propagation from the fronts present at the time of the shock, but the pathways of these fronts should be altered by the shock. 3) The direct excitation hypothesis postulates that the shock potential gradient field could have been strong enough to directly excite tissue beneath the plaque. Since the tissue directly excited should be that which is most recovered, it should include the tissue about to be excited by the activation fronts present at the time of the shock; therefore, these activation fronts should be halted by the shock. Thus, tissue between the activation fronts present at the time of the shock and the activation fronts just after the shock should be directly excited by the shock, and the activation fronts after the shock should arise from the border of this directly excited region. 4) The triggered focus hypothesis postulates that the shock potential gradient field could have been strong enough to extinguish activation fronts present in the tissue beneath the plaque by a combination of direct excitation and prolongation of refractoriness and to trigger activity that gives rise to new activation fronts some time after the shock.

To test the first two of these hypothesized mechanisms, it is necessary to 1) map the sequence of activation during fibrillation, 2) predict the spread of activation for a short time into the future during fibrillation, 3) determine if activation fronts after the shock arise by propagation from the fronts present at the time of the shock, and 4) determine if the course of the activation fronts after the shock is the same as or different from the course predicted if no shock had been given. In a previous study from our laboratory that attempted to accomplish these goals, activation sequences were mapped in three dimensions with 40 transmural needles spread 5 mm apart on which the recording electrodes were mounted. On the one hand, these needles were so closely spaced that they could have changed the electrical activity within the mapped region, yet on the other hand, their spacing was so far apart that activation fronts less than 5 mm in size would not have been detected. The electrodes in the present study were more.
closely spaced on the epicardium; therefore, activation fronts greater than approximately 3 mm in size should have been recognized. Although the previous study included only 20 defibrillation episodes in which the earliest activation after the shock arose from within the mapped region,27 171 such episodes were observed in this study because we lowered the potential gradient primarily within the mapped region, which caused early activation to originate from the region in a majority of the episodes. Episodes in which the earliest recorded activation after the shock was at the periphery of the mapped region were excluded, since such activations could have been conducted into the mapped region from somewhere outside.

Knowing the location of the low gradient region and, hence, the location of earliest postshock activation allowed us to concentrate recording electrodes in this region with sufficient density to record the complex spread of activation during fibrillation immediately preceding the shock. As was found in the previous study with wider electrode spacing,27 we observed a high degree of repeatability from cycle to cycle in the right ventricle after 10 seconds of ventricular fibrillation (Figures 4–8, panels A–C). The repeatability was sufficient to allow us to estimate the activation sequence for 50–100 msec into the future if no shock was given to alter it. In no case did an activation front continue unaltered through the mapped region after a successful defibrillation shock (Figures 4 and 5). In most episodes of failed defibrillation, activation sequences were also markedly changed after the shock (Figures 6–8). No activation complexes were detected for 59 ± 14 msec for monophasic shocks and 44 ± 18 msec after biphasic shocks (Table 3), which is much longer than the time required for the electrodes and mapping system to recover. This long time interval indicates that activation fronts were absent or were propagating very slowly and thus remained undetected between recording electrodes, suggesting that they covered a distance of less than a few millimeters during this time. Since the postshock early sites of activation were frequently more than a centimeter away from the locations of the activation fronts present at the time of the shock, this finding suggests that the activation fronts after the shock did not arise by propagation from the activation fronts present at the time of the shock, which contradicts the first two hypotheses given above (i.e., that activation fronts present at the time of the shock continue altered or unaltered after successful or unsuccessful shocks, respectively).1,2 This finding, which has been reported previously,27 was extended in the present study to include both monophasic and biphasic shocks and was shown to occur even at a potential gradient much less than that required for defibrillation (e.g., at less than 2 V/cm for a monophasic waveform that requires approximately 5 V/cm for defibrillation).

Unidirectional activation was observed after approximately two thirds of successful and unsuccessful defibrillation shocks (Table 2). Early sites for unidirectional activation patterns tended to be near the end of their absolute refractory period at the time of the shock. This assumption is made because the time between the shock and the previous activation just before the shock at these sites was 61 ± 18 msec for the 10-msec monophasic waveform and 65 ± 12 msec for the 5/5-msec biphasic waveform (Table 3). These values are similar to the values recently reported as the absolute refractory periods during ventricular fibrillation in dogs for shock fields of 5 V/cm for waveforms of shorter duration, 62 ± 5 msec for a 5-msec monophasic waveform, and 67 ± 7 msec for a 2.5/2.5-msec biphasic waveform.31 These considerations support the direct excitation hypothesis, which postulates that, on the side of the early postshock site away from which activation propagated unidirectionally, tissue could have been directly excited by the shock. This tissue could have been directly excited because it was slightly more recovered or the shock field was slightly stronger than the tissue at the early postshock site. The directly excited region would then be able to activate the adjacent site of early postshock activation after the shock, and conduction would propagate unidirectionally away from this region.6

The observation of a focal activation pattern following one third of the defibrillation episodes (Figure 8) conflicts with the direct excitation hypothesis, however, and agrees with the triggered activation hypothesis, which postulates that the shock could trigger the occurrence of new activation fronts. The triggered activation mechanism could also explain the pattern of unidirectional postshock activation, if block occurred on one side of the focus. Compared with the unidirectional activation pattern, the preshock interval is shorter and the postshock interval is longer at the postshock early activation site for the focal activation pattern (Table 3). An alternative explanation for these findings is that the focal activation pattern is similar to the unidirectional activation pattern, with conduction propagating away from a region directly excited by the shock, except that the directly activated region is not epicardial but is intramyocardial. If so, the unidirectional activation pattern could appear focal as it breaks through from below to create an early postshock activation site on the epicardium.32 The postshock interval would be longer (and perhaps the preshock interval would be shorter) for this early site, since an activation front would have had to travel for some period of time from the intramural border of the directly excited region to the epicardium. This interpretation supports the direct excitation hypothesis. Contrary to this interpretation is the finding that a few focal activation patterns have also been reported with three-dimensional mapping.27

Deciding between the direct excitation and focal activation mechanisms may require multiple simultaneous recordings of the transmembrane potential.33 Whatever the mechanisms for the unidirectional and focal activation patterns, they probably involve a complex interaction of the shock potential gradient field with the state of the tissue at the time of the shock. This is indicated by the fact that the preshock intervals at the sites of early postshock activation were not independent of the shock but occurred primarily during a certain portion of the cell cycle (Table 3). In addition to direct excitation, this complex interaction probably also includes prolongation of the action potential duration and refractory period without giving rise to a full new action potential.34–37 Such action potential prolongation has been shown to be induced by defibrillation shocks during ventricular fibrillation.35,38 We found that the sum of the preshock and postshock intervals at the early site of postshock activations for all shocks (116 msec for monophasic shocks and 108 msec for biphasic shocks,
Table 3) was longer than the mean cycle length during fibrillation just before the shock (101 msec for monophasic shocks and 96 msec for biphasic shocks). This suggests that action potential prolongation occurred at the early postshock activation site, which prolonged refractoriness for a short time.

Comparison of Effects of Monophasic and Biphasic Shocks

Biphasic waveforms have been postulated to defibrillate better than monophasic waveforms because they cause less detrimental effects in regions of high potential gradient. This study indicates that biphasic waveforms also have beneficial effects in regions of low potential gradient and thus that the minimum potential gradient required for defibrillation is decreased. The biphasic waveform required only 2.7±0.3 V/cm to achieve approximately 80% defibrillation success, whereas the monophasic waveform required 5.4±0.8 V/cm (Figure 3). Since the minimum potential gradient that must be achieved is less for the biphasic than for the monophasic waveform, weaker shock voltage and energy are required to achieve this minimum potential gradient.

One possible reason for the increased defibrillation efficacy of biphasic waveforms is that the stimulation threshold is lower for biphasic than monophasic waveforms. This idea is supported by the smaller minimum potential gradient required for defibrillation with the biphasic waveform in this study. However, another finding does not support this idea: the preshock interval at the site of earliest postshock activation was longer for biphasic than monophasic shocks (Table 3). This indicates that the tissue at the early postshock activation site was more recovered and hence less refractory for the biphasic shocks, suggesting that the biphasic waveform is less able to stimulate relatively refractory myocardium than is the monophasic waveform.

Other possible reasons for the increased defibrillation efficacy of biphasic over monophasic waveforms could be either 1) that the biphasic waveform is less likely to give rise to activation fronts after the shock or 2) that the activation fronts that do arise after biphasic shocks are more likely to halt after a few cycles rather than to reinitate fibrillation. This study suggests that both reasons may be true. This can best be seen by analyzing the potential gradient level at which the biphasic waveform has a high probability of defibrillation success and the monophasic waveform has a low probability of success (G2, the next to lowest gradient level in Figure 3). At this gradient level, biphasic shocks were less likely to give rise to activation fronts originating beneath the plaque after the shock. As shown in Table 2, only 23% of all successful and unsuccessful defibrillation episodes with a G2 level biphasic shock exhibited early sites of postshock activation in the mapped region compared with 53% of monophasic G2 level shocks. Yet the activation fronts that did appear after biphasic shocks were more likely to terminate after a few cycles rather than to reinitate fibrillation. As also shown in Table 2, only 31% of biphasic G2 episodes with early sites of postshock activation were unsuccessful compared with 79% of monophasic G2 episodes. Thus, the data provide evidence for both explanations.

It might be thought that the reason the postshock activation fronts die out without reinducing fibrillation more often after biphasic shocks than after monophasic shocks is because the patterns of activation formed by these fronts are different. This was not true; the incidence of focal and unidirectional activation patterns was not significantly different for the two waveforms (Table 2). For a given waveform, the longer the postshock interval, the greater the chance of successful defibrillation. Thus, it is surprising that activation fronts following biphasic shocks were more likely to halt fibrillation without reinitiating it than were activation fronts following monophasic shocks, because the mean postshock isoelectric intervals were shorter following biphasic than monophasic successful shocks (Table 1). Since the activation fronts arose in more recovered tissue after biphasic shocks, as indicated by their longer preshock intervals (Table 3), perhaps the activation fronts were more likely to halt before they encountered refractory tissue that could lead to block and reentry.

Conclusions

By creating different levels of potential gradient fields in a small region and mapping activations in this region with closely spaced electrodes, the study demonstrated that a low potential gradient in less than 10% of the ventricular myocardium can result in the resumption of fibrillation. Unsuccessful defibrillation shocks that generate potential gradients of at least 1–2 V/cm fail because the shock gives rise to new activation fronts that cause fibrillation to be reinitiated, even though the shock electric field halts all of the activation fronts during fibrillation. Defibrillation efficacy depends on the potential gradient, and this relation differs for different shock waveforms. An 80% chance of success of defibrillation requires a potential gradient field of approximately 3 V/cm for the biphasic waveform and 5 V/cm for the monophasic waveform tested. The minimum potential gradient for the prevention of postshock activation fronts is 5 V/cm for either waveform.

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Epicardial mapping of ventricular defibrillation with monophasic and biphasic shocks in dogs.

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