Effect of Nontransmural Necrosis on Epicardial Potential Fields
Correlation With Fiber Direction

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The effect of nontransmural necrosis on epicardial potential distributions was studied in 13 dogs. In previous studies, left ventricular epicardial pacing generated epicardial potential maps at QRS onset with a negative central area and two positive areas that faced the portions of the wavefront propagating along fibers. Subsequently, the positive areas expanded in a counterclockwise direction by 90° to 120°. In those studies, the rotary expansion of the positive areas was tentatively attributed to the spread of excitation through deep myocardial layers, where fiber direction rotated counterclockwise from epicardium to endocardium. To test this hypothesis, we tried to interrupt the counterclockwise expansion of the positive area by creating localized, nontransmural necrosis at various depths in the left ventricular wall by injection of formalin or application of laser energy. Epicardial potential maps were obtained from a grid of 12×15 electrodes on a 44×56-mm area. Epicardial pacing from selected sites generated epicardial maps in which some positive areas were missing compared with controls. The direction of the straight line joining the pacing site to the site of missing positivity correlated well with the average fiber direction in the necrotic mass (r=0.82, p<0.01). Angle between epicardial fiber direction and the straight line described above correlated well with the average depth of the necrosis, expressed as percent of the wall thickness (r=0.95, p<0.01). These data support the hypothesis that the counterclockwise expansion of the epicardial positivity occurring after epicardial pacing results from excitation spreading along deep fibers. The findings are consistent with the oblique dipole layer model of the excitation wavefront. The results may be useful for localizing nontransmural necrosis from epicardial maps. (Circulation 1990;82:2115–2127)

In previous studies,1–6 epicardial pacing of exposed dog ventricles generated epicardial potential distributions at the beginning of QRS with a negative central area and two potential maxima. The direction of the straight line joining the two maxima correlated well with the direction of subepicardial muscle fibers near the pacing site.1–6 This finding is consistent with the “oblique dipole layer” model of the excitation wavefront.7 The model assigns greater dipole strength per unit area to the portions of a wavefront that propagate along fibers (axial component) than to those that propagate across fibers. The model also predicts that, in the experimental conditions specified above, positive potentials will be generated only in those areas toward which the wavefront is spreading along fibers.8

In the experiments referred to above,5 the two positive areas observed at QRS onset expanded counterclockwise (CCW) by 90–120° from 10 to 30–70 msec into QRS, and new maxima appeared in the expanding positive areas (see Figure 4 in this paper). Those investigators5 tentatively interpreted the CCW expansion as being the epicardial projection of a rotating deep positivity, generated by the excitation wavefront as it propagated along deep fibers whose direction rotates CCW from epicardium to endocardium.9,10 CCW rotation of the intramural elliptical isochrones at increasing intramural depths after right ventricular epicardial pacing was shown by Frazier et al.12 It is reasonable to expect that the associated potential distribution should also exhibit

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some kind of CCW rotation, although the amount of rotation may be different for fiber direction, isochrone pattern, and potential distribution for reasons explained in Frazier et al10 and in the “Discussion.” In the present study, we tested the above interpretation by locally destroying some of the superficial or deep fibers that supposedly participated in generating the rotating epicardial positivity. We expected that, for properly selected pacing sites, a subepicardial necrosis would suppress one of the two initial maxima and the initial part of the CCW expansion of the positivity. According to the same reasoning, intramural and subendocardial necrosis would suppress later portions of the expanding epicardial positivity. We also expected that the position of the suppressed positivity within the expanding positive area would rotate CCW with increasing intramural depth of the necrosis, reflecting the loss of deeper and later portions of the rotating intramural positivity. To test the validity of this reasoning, we recorded left ventricular epicardial potential maps while pacing from various epicardial sites before and after inducing nontransmural, small necroses at various intramural depths in the left ventricular wall of exposed dog hearts. The necrosis was produced by laser energy or by formalin injection into the ventricular wall. The results were consistent with our expectation and supported our interpretation of the CCW expansion of the epicardial positivity during QRS.

**Methods**

*Creation of Necrosis and Data Acquisition*

Experiments were performed in 13 dogs weighing 20–28 kg and anesthetized with sodium pentobarbital (30 mg/kg). The heart was exposed by a left thoracotomy through the fifth or sixth intercostal space and suspended in a pericardial cradle. Respiration was maintained with a pump respirator. The sinus node was crushed, and the right or left atrial appendage was driven at 360–400-msec cycle lengths. One hundred eighty unipolar silver electrodes were mounted on a nylon sock that covered most of the anterolateral left ventricular surface except the apex (Figure 1A). The electrodes were arranged in a 12×15 grid with 4-mm spacing between columns and rows (Figure 1A, B). The nylon sock also carried 20 pairs of bipolar electrodes that were used for ventricular pacing (see Figure 11). During data acquisition, the sock was kept moist with saline so that a very thin layer of fluid covered the heart surface. Electrograms were simultaneously recorded from the electrode array, multiplexed, and digitized at 1,000 samples/sec with a 192-channel acquisition system. A Wilson central terminal was used as the reference electrode for recording. Control recordings and recordings after inducing the necrosis were obtained during simultaneous pacing of the atrium and of each stimulating electrode on the sock. Stimulation was performed by delivering current pulses of 2 msec at twice diastolic threshold.

Laser energy or formalin was used for inducing nontransmural necrosis. There were three types of necrosis (Figure 2). In two of 13 dogs, a laser-induced necrosis was made on the epicardium. A 0.9-mm diameter quartz core fiber (model 8200, Moleclectron Medical) was used for this purpose. Laser energy was supplied by a Nd:YAG (neodymium, yttrium, aluminum, garnet) laser (model 8000, Moleclectron Medical). Energy used was 50 and 100 J. In four of 13 dogs, 37% formalin was used for inducing limited intramural necrosis. A small amount of formalin (0.3–0.5 ml) was injected with a very fine needle (Tuberculin needle) from the epicardium in the area covered by the nylon sock. The depth of the injection and the amounts of formalin were such that the necrosis did not extend to the epicardium or endocardium. In seven of 13 dogs, laser energy was used for producing a necrosis on the endocardial surface (Table 1). A 5F catheter introducer was inserted into the left ventricular cavity through the right ventricle and the inter-
ventricular septum. The same type of laser fiber used for inducing subepicardial necrosis was inserted into the introducer and positioned with the tip touching the endocardial surface. Laser energies of 50–399 J were delivered to induce various extents of subendocardial necrosis. The position of the fiber tip was verified by fluoroscopy.

To avoid the interference of injury currents, we obtained recordings 2 hours after inducing the necrosis, when the ST-T shifts had disappeared almost completely.

**Data Analysis**

The 180 simultaneously recorded signals were gain and baseline adjusted. The electrograms were plotted, and their quality was evaluated. Missing or poor electrograms were replaced by the mean of the signals recorded by the surrounding electrodes. Then, epicardial potential maps were displayed for every msec in the QRS. Maps were displayed in the format shown in Figure 1B. Isopotential contours were drawn at 10 equal voltage intervals for each polarity using linear interpolation. This format facilitates recognition of the extrema.

Two hours after inducing the necrosis, some of the dogs showed a shortened QRS duration, as measured in the power curve, which displays, for every instant, the root mean square value of all voltages simultaneously recorded from the 180 sock electrodes. The amount of shortening ranged from 0 to 12 msec (average, 6.5 msec). The reason for the shortening was unclear. When the shortening was more than 5% of the control QRS duration, we normalized QRS durations. Corresponding “control” and “necrosis” time instants were determined by using the following expression: \( Y = X \) (QRS duration after injury divided by QRS duration in control state) where \( Y \) is time after stimulus (msec) in “necrosis” map sequence, and \( X \) is time after stimulus in “control” map sequence. Fractions of 1 msec were adjusted to the

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**Figure 2.** Cardiac sections showing the lesions (black areas) produced by laser (cases 1,2,7–13) or formalin (cases 3–6). All sections are oriented as follows. Top, posteroinferior wall of left ventricle; bottom, anterior wall of left ventricle. Section 11 depicts a portion of the posteroinferior wall of the left ventricle. Sections have been cut approximately midway between apex and base of left ventricle except section 12, which is closer to the base.

**Table 1. Type and Extent of the Necrosis Made by Laser and Formalin**

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of the necrosis</th>
<th>Necrosis size (mm)</th>
<th>Laser energy used (J)</th>
<th>Formalin injected (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subepicardial</td>
<td>9 x 9</td>
<td>3.5</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>Subepicardial</td>
<td>15 x 12</td>
<td>6</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>Intramural</td>
<td>5 x 5</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Intramural</td>
<td>10 x 10</td>
<td>9</td>
<td>0.3</td>
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<tr>
<td>5</td>
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<td>10 x 10</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>Intramural</td>
<td>11 x 11</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>Subendocardial</td>
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<td>2.5</td>
<td>50</td>
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<td>10 x 10</td>
<td>13</td>
<td>199</td>
</tr>
<tr>
<td>11</td>
<td>Transmural</td>
<td>10 x 10</td>
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<td>399</td>
</tr>
<tr>
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<td>Subendocardial</td>
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<td>10</td>
<td>399</td>
</tr>
<tr>
<td>13</td>
<td>Subendocardial*</td>
<td>13 x 14</td>
<td>12</td>
<td>399</td>
</tr>
</tbody>
</table>

*Part of the papillary muscle was involved.
Figure 3. Plot of fiber orientation versus intramural depth in the left ventricular wall of one dog.

nearest millisecond. This equation enabled us to compare “control” and “necrosis” maps from corresponding phases of activation.

Analysis of the isopotential maps was performed by comparing the location and size of the positive areas before and after necrosis. A procedure for evaluating the missing positivity is described in the “Results.”

Histopathology

After the animals were killed, the hearts were fixed in 10% buffered formalin. All hearts were subjected to gross examination for locating the necrotized tissue. The heart was cut into slices along lines parallel to the atroventricular sulcus. The necrotized regions were revealed by the presence of an area of black or gray tissue. Cubic blocks of normal tissue (10×10 mm×transmural thickness) and blocks including the necrosis with neighboring intact tissue were excised. The specimens were embedded in gelatin and sectioned parallel to the epicardium. The sections were 20 μm thick. Every 25th section was stained with hematoxylin and eosin and photographically enlarged. Fiber directions (relative to one side of the section) were measured at four different sites in each stained section and were averaged. Fiber directions versus intramural depth were plotted on graphs by assigning a value of 0° to the direction of epicardial fibers (Figure 3).

Because fiber direction in the necrotic regions was often difficult to determine, we measured fiber directions (with respect to epicardial fibers) near the outer and inner ends of the necrosis, and we took the mean of the two directions as an index of the average fiber direction in the necrosis (Table 2). We also determined the intramural depth of the inner and outer border of the necrosis, and we took the mean of the two depths as a measure of the depth of the center of the necrosis. This depth was normalized, that is, was expressed as a percentage of the total wall thickness at the site of necrosis excluding the papillary muscle when present (Table 2).

Results

Necrosis Produced by Laser Energy and Formalin

The epicardial lesions made by laser consisted of a central vaporized core surrounded by a dark necrotic tissue whose border was easy to identify. The lesions on the endocardium did not have the vaporized crater. However, the necrotized tissue was revealed by a darkened endocardial area and by a dark gray region in the wall. These findings were consistent with a previous report and enabled the border of most lesions to be identified. In the few cases in which the border of the lesion was not distinct, examinations were performed microscopically. Formalin-induced lesions were similarly revealed by the presence of a dark gray region with a clear-cut border. Diagrams of the lesions made by laser and formalin are shown in Figure 2. Table I shows the dimensions of the necrotic areas.

Epicardial Potentials

As shown in previous reports, epicardial pacing gave rise to epicardial potential distributions at QRS

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of necrosis</th>
<th>AP (°) of maxima flanking gap</th>
<th>Angular position (°) of bisector*</th>
<th>Fiber direction (°) at border of necrosis</th>
<th>Depth of necrosis border (mm)</th>
<th>Ventricular wall thickness at necrosis (mm)</th>
<th>Normalized depth of center of necrosis (% of wall thickness)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subepicardial</td>
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<td>40</td>
<td>20</td>
<td>0</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Subepicardial</td>
<td>0</td>
<td>70</td>
<td>35</td>
<td>0</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Intramural</td>
<td>35</td>
<td>95</td>
<td>65</td>
<td>25</td>
<td>65</td>
<td>45</td>
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<tr>
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<td>Intramural</td>
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<td>100</td>
<td>67.5</td>
<td>25</td>
<td>50</td>
<td>37.5</td>
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<tr>
<td>5</td>
<td>Intramural</td>
<td>20</td>
<td>90</td>
<td>55</td>
<td>25</td>
<td>80</td>
<td>52.5</td>
</tr>
<tr>
<td>6</td>
<td>Intramural</td>
<td>20</td>
<td>95</td>
<td>57.5</td>
<td>25</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td>8</td>
<td>Subendocardial</td>
<td>35</td>
<td>110</td>
<td>72.5</td>
<td>30</td>
<td>95</td>
<td>62.5</td>
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<tr>
<td>9</td>
<td>Subendocardial</td>
<td>30</td>
<td>100</td>
<td>65</td>
<td>40</td>
<td>83</td>
<td>61.5</td>
</tr>
<tr>
<td>10</td>
<td>Subendocardial†</td>
<td>20</td>
<td>120</td>
<td>70</td>
<td>20</td>
<td>130</td>
<td>75</td>
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<tr>
<td>13</td>
<td>Subendocardial†</td>
<td>40</td>
<td>115</td>
<td>77.5</td>
<td>25</td>
<td>90</td>
<td>57.5</td>
</tr>
</tbody>
</table>

AP, angular position.
*Angle ASD in Figure 10.
†Part of the papillary muscle was involved.
As with onset with a negative area close to the pacing site and two positive areas with two maxima located along a line parallel to epicardial fiber directions (Figure 4, 10 msec). Later into QRS, the two positive areas expanded CCW in all the experiments and finally surrounded the central negative area on both sides. As an example, Figure 4 shows a 110° CCW expansion-rotation of the upper positive area. Other examples are given in Figure 5 (total rotation, 120°) (see also Figure 8). In all cases, one or more new maxima appeared in the positive areas as they expanded CCW (Figure 4, 45 msec; Figure 8, control, 48 msec).

The CCW expansion of the positive areas during QRS was always continuous; that is, no negative islands interrupted their progressive CCW expansion, even when multiple maxima developed in a single positive area (Figure 4, 45 msec; Figure 8, control, 48 and 49 msec). We attempted to describe the CCW expansion-rotation of the positivity in a semiquantitative way by measuring the CCW rotation of the maximum around the pacing site during QRS, starting from its initial position just after the stimulus, which was defined as “0°.” The angles, measured as explained above, were called “angular positions of the maximum.” When two or more maxima were present in the positive area at a given time instant (as in Figure 4, 45 msec), their angular positions were averaged. Figure 6 shows the CCW rotation of the maximum during QRS as measured after pacing 108 epicardial sites in 13 dogs. Total rotation was 100±15° (SD). Typical examples of CCW expansion of the positivity are depicted in Figures 4 and 5, which show two series of potential maps obtained while pacing the left ventricular epicardium at site S (Figure 4) and S’ (Figure 5) in the same heart (case 1). At 10 msec after stimulation, two maxima and a single minimum were observed near the pacing site. The straight lines connecting the pacing site with the maxima were nearly parallel to the local direction of the epicardial fiber (arrow). In the negative area, an
array of densely packed negative isopotential lines revealed the approximate position of the wavefront. Positive potentials spatially preceded the wavefront where it propagated along the direction of the epicardial fibers. Conversely, negative potentials were observed in the areas toward which epicardial excitation propagated across fibers. As the wavefront advanced, the upper positive area expanded CCW forming a C-shaped positive ridge (Figure 4, 40–60 msec). At 20, 30, and 40 msec, the angular positions of the upper maximum were 10°, 22°, and 25°, respectively. At 45 msec, a new maximum appeared (Figure 4, 45 msec) so that two maxima were simultaneously present for 2 msec. The averaged position of the maximum at 45 msec was 43°. In most cases, the position of the maximum changed rapidly after 40 msec. For example, in Figure 4, the angular position of the maximum shifted from 25° to 80° between 40 and 50 msec. Then, the maximum moved out of the area explored (60 msec). Another pacing site in the

**Figure 5.** Isopotential maps for the same experiment as in Figure 4 but with different pacing site (S'). Total rotation of maximum is 120°.

**Figure 6.** Plot of rotation of maximum as a function of time after pacing. Mean values and standard deviations are shown in 10-msec increments. Dotted lines show mean±2SD. Data relate to a total of 108 pacing sites in 13 dogs.
same dog brought about angular positions of the upper maximum of 10°, 80°, 105°, and 115° at 20, 50, 60, and 70 msec, respectively (Figure 5).

**Effect of Necrosis**

All hearts with subepicardial, intramural, or subendocardial lesions exhibited some loss of positivity compared with controls during the CCW expansion of the positive areas. The missing positivity was replaced by a localized negative area. Loss of positivity in dogs with subepicardial necrosis occurred in the initial stages of QRS (Figure 7; 12 and 15 msec). In dogs with intramural or subendocardial necrosis, the loss of positivity occurred later in QRS and produced a gap in the expanding positive area (Figure 8, 49 msec, right column).

**Subepicardial necrosis.** In two dogs, a circumscribed subepicardial necrosis was induced by laser energy. When the heart was paced from sites so that the line connecting the pacing site to the center of the necrosis was approximately parallel to the epicardial fiber direction, the relevant positive area did not appear in the early stages of QRS and was replaced by a negative area (Figure 7, 12 msec). A potential maximum appeared later in a different position (Figure 7, 15 msec), and the positive area surrounding the maximum started its CCW expansion from that new position. To evaluate the loss of positivity in these cases, we drew two segments on the maps, joining the pacing site to the site of the missing maximum (Figure 10, subendocardial necrosis, segment S-B) and to the delayed maximum (segment S-C). Segment S-A indicates the direction of the epicardial fibers that, in the case of epicardial necrosis, coincides with S-B. Segments S-B and S-C roughly delimited the area of missing positivity. The value of the angle B-S-C between the two segments (angle β) was taken as an index of the amount of missing positivity (Figure 10). The bisector of the angle between the two segments (segment S-D) was
Intramural and subendocardial necrosis. In four dogs, an intramural necrosis was induced by injecting a small amount of 37% formalin into the left ventricular wall. In seven dogs, a subendocardial necrosis was created by delivering laser energy on the endocardium by an intracavitary catheter (Figure 2). Only data from four of these seven dogs were used for reasons explained below. In all eight dogs considered here, epicardial maps recorded while pacing from selected epicardial sites showed some loss of positivity compared with controls (Figure 8, 45 msec). The loss of positivity appeared as early as 20 or 25 msec after the stimulus when the outermost border of the necrosis was close to the epicardium (e.g., case 5, Figure 2). Later maps invariably exhibited a gap in the expanding positive area (Figure 8, 49 msec; Figure 9, 56 msec). Such a discontinuity never occurred in normal hearts (see controls in Figures 8 and 9). The negative area was always located along or near a straight line passing through the pacing site and the epicardial projection of the necrosis (Figure 8, 49 msec; Figure 9, 56 msec; Figure 10). The gap persisted for 3-7 msec and changed in shape and size during this time interval. To evaluate the location and amount of missing positivity in a semiquantitative way, we drew two segments joining the pacing site to the two maxima flanking the gap (Figure 10, intramural necrosis). The two segments encompassed an area of decreased or missing positivity. Here again, the angle between the two segments (angle B-S-C or β in Figure 10) was taken as an index of the amount of missing positivity, and the bisector of angle β (segment D in Figure 10) indicated the angular position of the center of missing positivity (angle α). Angle α was greater in dogs with subendocardial necrosis than in dogs with intramural necrosis (Table 2). Also, the gap occurred later in QRS in dogs with subendocardial necrosis (56 msec in Figure 10 versus 49 msec in Figure 8).

The number of pacing sites bringing about a loss of positivity varied between two and five in dogs with intramural necrosis (five sites in Figure 11) and between two and four in dogs with subendocardial necrosis. Because, for a given necrosis, the amount (angle β) and position (angle α) of the missing positivity varied for different pacing sites (Figure 11), we took the widest angle β as an index of the highest
amount of missing positivity in a particular experiment (see star in Figure 11, relating to a case of intramural necrosis). The corresponding bisector (angle α) was taken as an index of the angular position of the center of missing positivity. In a given dog, the value of angle "α" was stable for the entire duration of the gap (3–7 msec).

All four cases with intramural necrosis and four of seven cases with subendocardial necrosis exhibited the potential patterns described above. Two cases with subendocardial necrosis were discarded because the major necrosis was in the septum (case 12) or in the posterior wall (case 11), areas not sampled by the electrode array. Another case with superficial necrosis in a papillary muscle (case 7) was also discarded. The maps of that case showed some delay in the expansion of the positive area compared with controls but no new negative area.

In summary, four cases (cases 3, 4, 5, and 6) with intramural necrosis, four cases (cases 8, 9, 10, and 13) with subendocardial necrosis, and two cases with subepicardial necrosis were used for statistical analysis.

**Histological Findings: Correlation With Potential Patterns**

The overall cellular arrangement in the explored area was similar in all the hearts, with some individual variability. Epicardial fiber directions were approximately perpendicular to the left anterior descending coronary artery. Serial sections of the tissue at 0.5-mm intervals at various locations in the explored area showed an epicendocardial CCW rotation of fiber direction (Figure 3). The total rotation varied between 75° and 125° among specimens. These figures are consistent with data from the literature.9,10 Comparison of electrical and histological findings showed a good correlation between the angular position of the center of missing positivity (angle α) and the average fiber direction in the necrosis (r=0.82, p<0.01) (Figure 12A). A good correlation was also found between the position of the gaps (angle α) and the normalized depth of the center of necrosis (r=0.95, p=0.01) (Figure 12B). This was not unexpected because fiber direction correlates with intramural depth.9,10

**Discussion**

The purposes of this investigation were 1) to describe and interpret epicardial potential patterns associated with ventricular, nontransmural necrosis, 2) to test previous hypotheses on the origin of the CCW expansion of positive epicardial areas observed in normal dogs after epicardial pacing, and 3) to evaluate the possibility of detecting intramural necrosis from epicardial potentials.

In accord with previous observations,5 this study confirmed that pacing the ventricular epicardium of normal exposed dog hearts generated epicardial potential maps at QRS onset with a central negative area and two maxima surrounded by two positive areas. The axis joining the two maxima was parallel to the direction of the subepicardial fibers. We also confirmed the CCW expansion of the positive areas, which occurred in later stages of QRS, from 10 to 70 msec after the stimulus, and which amounted to 100±15° (SD). As previously suggested,5,8 the early pattern with two maxima and the subsequent CCW expansion of the positive areas during QRS may be explained by the oblique dipole layer model of the excitation wavefront.5 This model predicts that positive potentials will be mostly found in those areas toward which the excitation wavefront is spreading along fibers. However, if the epicardial field were only affected by excitation spreading along the epicardial fibers, the positive area should move only along the direction of the subepicardial fibers during
the entire QRS interval and not expand CCW. Conversely, the appearance of new, CCW expanding positive areas later in QRS suggests participation of deep wavefronts in the genesis of epicardial potentials. Counterclockwise rotation of deep elliptical wavefronts after epicardial pacing has been demonstrated by Frazier et al\textsuperscript{12} as a result of rotating fiber direction with increasing intramural depth. Our results are consistent with the study by Frazier et al in that they show that some features of the epicardial field, namely the potential maxima, also rotate CCW as excitation reaches deeper intramural layers. However, the amount of rotation exhibited by the potential pattern may be different from that of the isochrones, whose rotation as a function of depth lags behind the rotation of the fibers.\textsuperscript{12} Intramural measurements are needed to define the correlation between the three types of rotation (fibers, isochrones, and potential patterns). Such studies are actually in progress at this institute. Previous studies\textsuperscript{5,6} showed that epicardial potentials are affected by deep wavefronts and by the direction of deep fibers through which excitation is spreading. In the light of the oblique dipole layer model, the CCW expanding positivity on the epicardium may be interpreted as the epicardial projection of a deep rotating positivity that arises when excitation spreads into deep myocardial layers, where fiber direction rotates CCW from epicardium to endocardium. If this interpretation is correct, we would expect an interruption in the CCW expansion of the epicardial positivity when we destroy a limited amount of intramural fibers and a suppression of the initial positivity when we destroy a limited amount of subepicardial fibers, provided we choose appropriate pacing sites.

The results of this study support the above interpretation of the early epicardial positivity and its subsequent CCW expansion during QRS. Epicardial necrosis actually suppressed the initial positive area and its maximum when the epicardial wavefront spread along fibers into the necrosis (Figure 7). Intramural necrosis brought about a loss of epicar-
dial positivity that occurred later in QRS and, still later, a localized gap in the CCW expansion of the positivity. The angular position of the gap, determined as explained in the “Results,” rotated CCW with increasing depth of the necrosis and correlated with average fiber direction in the necrotic area (and, by consequence, with the intramural depth of the necrosis) (Figure 12). Also, the gap occurred later in QRS for intramural than for subepicardial necrosis. All these findings are consistent with the previously suggested interpretation of epicardial potentials, based on the oblique dipole layer model of the excitation wavefront. From the viewpoint of possible clinical applications, our results showed that epicardial potential maps exhibit characteristic changes in dogs with nontransmural necrosis. Knowledge of these patterns may be useful for detecting intramural necrosis from epicardial maps, whether directly recorded or computed from body surface measurements with inverse procedures.

In assessing the validity of our conclusions, we must take into consideration the limits inherent in our experimental conditions.

1) Only epicardial potentials were measured in this study. Therefore, our interpretation of the results in terms of intramural events is based on indirect experimental evidence and should be substantiated by three-dimensional transmural mapping of isochrones and potentials, which should be performed before and after inducing the necrosis. Such studies are actually in progress at this laboratory. Also, stimuli of greater strength or deep stimulations would create intramural wavefronts that move directly into the necrosis and may, therefore, provide additional data to test the hypothesis.

2) Only a limited epicardial area was explored. Apical areas, where fiber architecture and myocardial structure are different from those existing in the region we studied, may behave differently. Also, our
procedure is insensitive to lesions in the interventricular septum.

3) Our interpretation of epicardial potentials is based on the assumption that only those portions of a wavefront that propagate along fibers generate positive potentials. According to the oblique dipole layer model,7 this contention is true if the wavefront is a closed surface or its rim is exposed to air. However, when the wavefront initiated from an epicardial pacing site reaches the endocardium, the wavefront is no longer a closed surface because it opens into the ventricular cavity that contains blood, a conductor of electricity. This situation makes the electrical field more complicated. Although the axial component is still predominant, epicardial potentials after endocardial breakthrough are also affected by the transverse component. This fact must be taken into account when interpreting the maps in the late phases of the QRS.

4) Finally, in our experiments, the gaps in the positive areas often appeared 40 msec after the stimulus or later, at a time when Purkinje involvement had probably occurred. The role of the Purkinje system in determining epicardial potentials after epicardial pacing, both before and after inducing a necrosis, was not investigated in this study and will be addressed in future studies, based on intramural recordings. However, the loss of positivity that invariably preceded the gaps often started well before excitation had reached the endocardium and was, therefore, related to the intramural spread of the primary wavefront.

With regard to the clinical implications, the results of the present study may provide useful criteria for locating nontransmural necrosis. Previous studies showed that subendocardial or intramyocardial regions play a role in the initiation and maintenance of monomorphic ventricular tachycardia.13 For the treatment of such reentrant tachyarrhythmia, surgical procedures to isolate the arrhythmogenic foci or routes are used.14,15 Catheter-mediated destruction of tissue using electrical discharge has also been tried.16 In these procedures, identification of the tissue as normal or necrotic is extremely important for both choosing the target and knowing the effect of ablation. A classifier based on the magnitude of the epicardial Q waves in dogs was reported by Laxer et al.17 The classifier detects the epicardial projection of intramural infarctions but does not reveal the depth of the necrosis. The same investigators reported that most of the misclassified electrodes were near the borders of the infarcts. The regions bordering an infarct are often the site of continuous diastolic activity and can induce tachycardia when prematurely stimulated.18,19 Identifying the border and the depth of damaged tissue are important issues, still unsolved to date. The method described here may be useful to assess the depth of the necrosis in the wall. However, it must be pointed out that the area of missing positivity is not the necrotic area itself. To locate the necrotic area, both the Q wave criterion and determination of the missing positivity may be necessary. The bisector of the angle that delimits the loss of positivity has been shown to pass through the epicardial projection of the necrosis. This criterion may also help to locate the injury. On the other hand, the geometry of an infarcted area is often irregular, unlike the clear-cut necrosis in this study. Additional studies with actual infarcts will be required to better evaluate the clinical implications of our findings.

This study validates several predictions of the oblique dipole layer model7 and contributes to our understanding of epicardial potential maps as reflecting intramural events. Although many problems remain unsolved, our study shows the usefulness of epicardial potential maps obtained during epicardial pacing for assessing intramural events and for determining the site and depth of nontransmural necrosis.

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