Activation Patterns in Healed Experimental Myocardial Infarction


The maximum amplitude of vector loops formed by summing orthogonally recorded bipolar electrograms has been shown to reflect the direction of activation in cardiac muscle. To investigate whether components of vector loops could provide information about different activation directions in local areas of myocardium, we correlated "instantaneous vectors" with isochronal activation patterns in an in vitro preparation of experimental myocardial infarction. In thirteen 3 mm×3 mm regions studied (from 11 tissues), at least 16 microelectrode impalements with a minimum density of 0.8 mm between sites were made. In seven situations in which notched, irregular, and prolonged duration electrograms were present, vector loops pointed in the same general direction throughout their entire time course. In these preparations, microelectrode impalements demonstrated only a single major direction of activation. In five of six areas in which multidirectional vector loops were present, two or more separate local directions of activation corresponded to the directions of the vector loop. Instantaneous vectors were then used to analyze propagation patterns in vivo in 10 animals with 2–4-week-old experimental myocardial infarction. Of 150 sites in the 10 animals, 13% contained more than one major local direction of activation. In 11 markedly abnormal sites, electrograms were recorded during pacing from four sites around the recording probe. When comparing electrogram characteristics from the four sites, a mean difference of 5.9 mV in electrogram amplitude and 19.1 msec in electrogram duration (coefficient of variation, 27% for amplitude and 22% for duration) was found. In only two of the 11 sites was it found that the same number of activation directions occurred from all pacing sites. We conclude: 1) Instantaneous components of vector loops accurately represent local directions of cardiac activation at differing times. 2) Most areas of experimental myocardial infarction have only one major direction of activation despite the presence of abnormal electrograms. 3) In some regions, however, two major local directions of activation can be identified within a relatively local area. 4) Geometric activation patterns in experimental myocardial infarction are markedly dependent on initial activation direction. (Circulation Research 1989;65:1698–1709)

Although tissues removed from animals that have undergone an experimental myocardial infarction procedure contain significant abnormalities of transmembrane potentials in the first few days after the infarction procedure, these abnormalities largely resolve within 2 weeks after infarction.1,2 Despite the presence of normal action potentials, slow and discontinuous conduc-
orthogonally bipolar electrograms to determine the direction of activation in cardiac tissue. These studies were based on using the maximum X-Y amplitude of a vector loop to identify a direction of activation, and only a single activation direction was analyzed for each loop. Although vector loops recorded from normal myocardial tissue were found to be smooth and pointing in a single direction, those recorded from areas of healed experimental myocardial infarction were notched, irregular, and occasionally pointing in more than one direction. We hypothesized that instantaneous vectors composing the vector loop might represent activation directions at different points in time in areas of healed infarction and provide insights into activation patterns in such areas that could not be obtained from examination of the electrograms alone. We undertook this study to 1) validate the ability of instantaneous vectors to represent local activation directions at different points in time and 2) apply this technique in vivo to characterize conduction patterns in healed experimental myocardial infarction.

Materials and Methods

Twenty-four normal mongrel dogs weighing 10–20 kg underwent occlusion-reperfusion experimental myocardial infarction as previously described. The chest was closed in a sterile fashion, and the animals were given careful postoperative monitoring including antibiotics and analgesics.

Electrogram Recording

Reference extracellular electrograms were recorded with bipolar Teflon-coated silver wire (0.5-mm interelectrode distance), amplified from 100–1,000 times, and displayed on an oscilloscope. Extracellular electrogram mapping was performed by use of custom-made electrodes with a 2-mm interelectrode distance containing two orthogonal bipolar pairs. Electrograms were recorded from these probes and amplified with a custom-made balanced amplifier (Bloom Associates, Narberth, Pennsylvania), filtered at 1 Hz to 1 kHz, and displayed on an oscilloscope.

Transmembrane potentials were recorded by standard microelectrode techniques with 3 M KCl-filled electrodes as previously described. Potentials were instantaneously differentiated by analog differentiation, and the action potential and its derivative were displayed on an oscilloscope. Data was recorded on 35-mm film and manually digitized with a computer and digitizing system (model 9836, Hewlett-Packard, Palo Alto, California). Activation times were determined to the nearest millisecond; action potential amplitude, to the nearest millivolt; and peak dV/dt, to the nearest 2 V/sec. Activation times for transmembrane potentials were determined at the time of maximum dV/dt electrogram peak.

Vector Methods

The technique for recording vector loops has been previously described. Briefly, orthogonal bipolar electrograms were recorded at a single site, amplified to exactly the same gain, and placed into the X and Y inputs of a standard oscilloscope (series 5000, Tektronix, Beaverton, Oregon). The maximum X-Y amplitude of the thus-created vector loop indicates the direction of local activation in cardiac tissue. An example of the creation of a hypothetical vector loop is shown in Figure 1.

In Vitro Studies in Area of Myocardial Infarction

One to 3 weeks after the infarction procedure, animals were anesthetized with intravenous sodium pentobarbital, the chest was opened via left lateral thoracotomy, and the heart was excised. Epicardial tissues approximately 2 cm×3 cm×2 mm were shaved from the excised heart. The tissues were placed in oxygenated Tyrode’s solution containing 1.6 mM calcium at 37° C. Tissues were paced at a cycle length of 1,000 msec by use of rectangular 2-msec pulses at twice diastolic threshold. Reference electrodes were placed on the opposite side of the tissue from the pacing electrodes. A total of 17 tissues from 13 animals were studied. One tissue lost excitability before an adequate number of impalements could be made. Impalements were made from a 3-mm×3 mm area from which a vector loop was recorded. At least 16 impalements, which allowed for a maximum average distance of 0.8 mm between sites, were required to consider a tissue suitable for study. Epicardial scarring in areas of interest prevented large numbers of impalements in five other tissues. Thirteen sites were studied in the remaining 11 tissues.

Extracellular electrograms and vector loops were recorded with the 2-mm interelectrode distance-mapping probe at 10–20 equally spaced sites approximately 2 mm apart throughout the tissue. After extracellular electrograms had been obtained, vector loops were examined for areas of interest as described below.

In Vivo Experiments

Ten other animals were used for in vivo experiments. One to 3 weeks after experimental myocardial infarction, the dogs were reanesthetized with sodium pentobarbital and ventilated with room air. The chest was opened via a median sternotomy, and a pericardial cradle was created. A 40-point plastic template plaque was sutured to the anterior surface of the left and right ventricles so that at least one corner of the plaque was over the area of experimental myocardial infarction. The plaque contained areas arranged in an 8×5 array with a 7.5-mm interelectrode distance between mapping sites along each axis. An average of 16 sites was located over the area of experimental myocardial infarction in each experiment.
FIGURE 1. Schematic diagram of a hypothetical vector loop recording. The four black circles indicate the four poles of the recording probe located on the surface of a tissue. The open arrow indicates the direction of epicardial impulse spread that in this idealized diagram is parallel to the long axis of myocardial fibers. The positive poles of the two bipoles are the rightward and upper poles. In the center of the diagram are unipolar electrograms recorded from each of the poles. These were derived from unipolar waveforms, published by Spach et al. The extracellular waveforms that will enter the negative poles of the difference amplifiers have been inverted. Note that the impulse first reaches the negative horizontal pole, the vertical bipoles simultaneously, and lastly the rightward positive pole. Since the y-axis electrodes are located in almost iso-potential areas, the bipolar y-axis records very little activity. The x-axis electrode records a triphasic deflection with a large positive component. The X and Y electrograms are then fed into the x and y axes of an oscilloscope. The positive rightward deflection corresponds to the direction of impulse propagation.

Protocol A

Activation mapping was performed during pacing from one side of the plaque via a bipolar stainless steel electrode at twice diastolic threshold at a pacing cycle length of 350 msec. Electrograms were amplified, displayed, photographed, and analyzed in a fashion similar to that described in the in vitro experiments.

Protocol B

After activation mapping was performed during pacing from one site, 11 areas with low amplitude prolonged-duration electrograms and abnormal vector loops were selected for analysis of activation during pacing from several sites. Bipolar pacing electrodes were placed 7.5 mm from the recording site at each of four sites 90° apart around the recording electrode. Thus, activation at an individual site could be examined when pacing adjacent to it from all directions around it.

Unidirectional Versus Multidirectional Vector Loops

We had previously observed two general patterns of vector loops in areas of experimental myocardial infarction. One type of vector loop contained notched, irregular, and multicomponent portions in which all the components pointed in the same general direction. In some of these areas, a single open irregular component was present. In other areas, several components separated by a return to the vector origin were present with all components pointing in the same general directions. Both of these types of vectors were considered to represent "unidirectional" vectors. In a second group of areas, multicomponent vectors with separate components pointing in directions more than 90° apart were present. We hypothesized that "multidirectional" vectors represented two distinct local directions of activation and that the unidirectional vectors represented slow and discontinuous conduction all proceeding in the same general direction. To verify this hypothesis, we subjected areas containing these patterns of vector loops to high density microelectrode impalements. Although we used 90° as an arbitrary cutoff to separate unidirectional from multidirectional vectors, the correlation between vector and isochronal activation directions was performed for a wide variety of angles.

To completely define conduction in areas of myocardial infarction, it might be argued that the activation of every individual cell must be identified because ingrowth of fibrous tissue could produce cell-to-cell irregularities in conduction. Since this is impractical, any description of activation must define some scale over which it operates. Far-field electrical activity can be recorded in extracellular electrograms if amplification gain is extremely large; thus, the amplitude of electrograms or vector loops analyzed will be a determinant of the area from which electrical activity is recorded and the degree of...
resolution of the technique. Electrograms recorded from infarcted regions by use of the vector probe averaged 14±11 mV in vivo, and thus, a 2 SD cutoff (for lower amplitude) was not possible. We chose 1 mV in vivo as an arbitrary amplitude cutoff to minimize the effects of distant activity on the local electrograms and, thus, on vector loops. As previously noted,7 electrogram amplitudes with the 2-mm interelectrode distance probe filtered at 1 Hz to 1 kHz are far larger than those recorded with other types of electrodes. Electrograms recorded in vitro are approximately one fifth of those recorded in vivo (unpublished results), and thus, we chose an amplitude cutoff of 0.2 mV in vitro.

In analyzing instantaneous components of vector loops (which were recorded using a variable gain to allow visualization of an entire loop), it was necessary to choose some amplitude cutoff below which components would be ignored. Thus, in defining multidirectional vectors, we considered instantaneous vectors with amplitudes greater than 1 mV in vivo and 0.2 mV in vitro. Vector loops with components of such amplitude more than 90° apart were considered to be multidirectional, and all others, unidirectional.

**Statistics**

Data were expressed as mean±SD. Variability in electrogram or vector characteristics at a single site during pacing from different directions was determined by use of a coefficient of variation.

**Results**

**In Vitro Studies in Infarcted Tissue**

A total of 13 sites were studied adequately (see "Materials and Methods"). Sequential activation maps obtained with an extracellular probe revealed occasional areas from which electrical activity could not be recorded. From the remainder of the tissues, low amplitude prolonged-duration electrograms associated with notched and multicomponent vector loops were recorded. Four hundred ten microelectrode impalements were made in all; mean action potential amplitude was 91.2 mV, and mean peak dV/dt was 111.7 V/sec. Action potentials were photographed only at a fast oscilloscope speed, and thus, data on action potential duration was not available.

Of 13 sites studied, seven had regions with single directional irregular vectors that were analyzed, and six had regions with vectors of more than one component direction (Table 1). To examine the correlation between vector morphology and activation patterns, multiple impalements were made in sites containing both unidirectional and multidirectional vectors. In the seven sites with a single directional vector, isochronal activation maps constructed from microelectrode impalements revealed

### Table 1. Summary of In Vitro Experiments

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Mean unidirectional vectors

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Mean of multidirectional vectors

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### Notes

- Vector loops with components more than 90° apart were considered multidirectional (Multi), and all others were considered unidirectional (Uni).

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**References**

slow and occasionally microscopically discontinuous conduction, all proceeding in the same general direction of activation.

An example of one such vector loop with two separate components pointing in the same general direction is shown in Figure 2. Figure 2, left panel, shows a map of microelectrode impalements obtained in the area where an extracellular vector loop was recorded. The shaded square indicates a region in which no viable cells could be identified despite repeated impalements. Impulses are proceeding rightward and upward in the area of the recording probe. However, conduction is somewhat irregular as indicated by the variable spacing between isochrones. In Figure 2, right panel, electrograms and a vector loop recorded from just above the shaded area in the left panel (activation time, 45 msec) are shown. The vector loop has multiple components, each pointing upward and rightward and corresponding to activation of regions below the shaded area, to the left of this area, and above the shaded area.

In five of the six areas in which multidirectional vectors were identified, microelectrode impalements revealed local activation directions corresponding to the different components of the multidirectional vector loop and located within 3 mm of the center of the extracellular recording electrode. In some of the sites, anatomic barriers were visible on the epicardium; however, in others no barriers were visible. Figures 3–6 present data from an experiment performed on a tissue removed from an animal with an 11-day-old myocardial infarction that exhibited a unidirectional vector (Figure 4), as well as multidirectional vectors (Figures 5 and 6), produced by differing activation directions around a visible blood vessel. Figure 3 shows activation times determined from microelectrode impalements during pacing from the upper right corner of the tissue. Impulses proceed slowly leftward and downward until they encounter the blood vessel (hatched...
FIGURE 4. Examples of vector loops, component bipolar electrograms (X and Y), and a plot of vector angle versus time, recorded from site 1 in Figure 3. Panel A: Electrograms recorded from site 1. These were wide and contained occasional minor notching. Panel B: An open vector loop with occasional notching and irregularity. The vector loop contains a single component and is thus a "unidirectional" loop. The midpoint of the open vector loop is directed leftward and downward. Panel C: Plot of vector angle versus time over the course of the recorded electrogram. The vector angle throughout this time proceeds leftward and downward, a direction that correlates with the general direction of the impulse spread proximal to the blood vessels as shown by the microelectrode isochronal map in Figure 3. A brief upward component is present from 22 to 24 msec.

FIGURE 5. Vector loop recorded at site 2 in Figure 3. This area is located just proximal to the blood vessel. Panel A: Two separate general components of the electrograms (X and Y), separated by what resembles an isoelectric period. Panel B: Corresponding vector loop with two distinct components (1 and 2). 1, component indicating activation direction proximal to the blood vessel; 2, a brief upward component proximal to the blood vessel; 3, component indicating activation direction distal to the blood vessel. Panel C: Plot of vector angle versus time over the course of the vector loop. See text for details.

The blood vessel appears to produce an area of block around which impulses spread in two directions to collide distal to the blood vessel. In addition to this area of impulse block, irregularity in conduction in local areas is present throughout the
tissue as indicated by the variable difference in activation times between areas of similar distance apart. Figures 4–6 show vector loops recorded at various locations within the tissue. Figure 4 shows a vector loop recorded to the left of the pacing electrode proximal to the blood vessel at position 1 in Figure 3. There is only one major component to the vector loop, and it all proceeds in the same general direction that corresponds to the leftward and downward direction of impulse propagation from the pacing electrode. Figure 5 shows a vector loop and component electrograms recorded from over the area of the blood vessel. The leftward and downward component (1) corresponds to the leftward and downward activation proximal to the blood vessel, and the rightward downward component (3) corresponds to activation distal to the blood vessel. The notching on the vector loop and electrograms as well as the brief positive component located between 20 and 25 msec (2) suggest microscopic discontinuities in conduction superimposed on areas of block produced by the blood vessel. Figure 6 shows an example of a vector loop recorded distal to the barrier. The component electrograms once again contain notching and irregularity and are separated by an isoelectric period. More than one activation direction is present both proximal and distal to the barrier. In Figure 6B, activation directions proximal to the barrier occurring from approximately 10 to 30 msec are indicated by components 1A and 1B of the vector loop. Activation patterns distal to the barrier are indicated by components 2A and 2B. In Figure 6C, a plot of vector angle versus time for this vector loop is shown. Each component correlates with an activation direction found in the microelectrode map shown in Figure 3. A general downward and leftward activation direction is found proximal to the vector loop. The brief upward component is likely caused by a small area of block and irregular conduction proximal to the barrier. This is indicated by the small arrow in Figure 3, but additional activation in an area not defined by microelectrode impalements may be responsible for a portion of this component. Activation distal to the barrier is complex as well. A collision is produced relatively near the recording electrode. Two separate components, one corresponding to activation rightward and downward from 56 to 62 msec is shown by component 2A. This corresponds to the microelectrode impalements and a thick arrow in Figure 3. At a slightly later time, from approximately 65 to 70 msec, impulses are proceeding upward and leftward corresponding to the other large arrow in Figure 3. Once again, an excellent correlation is observed between directions indicated by the microelectrode map and vector loops.

Figures 7 and 8 present examples of a correlation between an extracellular recorded vector loop and microelectrode impalements in an area of infarction and scar without visible blood vessels. Figure 7A shows bipolar extracellular electrograms and a vector loop recorded from the center of the area map of microelectrodes. The extracellular electrograms are abnormal, of prolonged duration, and markedly notched. The resulting vector loop is multidirectional with separate components pointing in different directions. In Figure 7B, representative microelectrode impalements from the region of extracellular recording are shown. Individual microelectrode impalements correspond to different components of extracellular electrograms.
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FIGURE 7. Example of extracellular electrograms (X and Y; panels A and B), a vector loop (panel A), and microelectrode recordings (panel B), obtained from a tissue removed from an animal with a 3-week-old experimental myocardial infarction. Microelectrode recordings were made beneath the area of the vector probe. Note that individual microelectrode recordings of action potentials (AP1–AP4) correspond to separate deflections seen on the bipolar electrograms. The measured action potential parameters were close to normal with an amplitude averaging 94 mV and a mean dV/dt of 110 V/sec. These impalements and electrograms are consistent with previous data demonstrating that asynchronous groups of cells in local areas produce separate deflections in irregular and fractionated electrograms. The vector loop contains at least three distinct components directed in different directions, labeled 1, 2, 3A, and 3B. See text for details.

FIGURE 8. Panel A: High density microelectrode map from the area in which the extracellular electrograms and vector loops shown in Figure 7 were recorded. The shaded areas indicated areas of whitish, visible scar in which no active responses could be demonstrated with microelectrode impalements. Thick arrows indicate directions of impulse spread around anatomic barriers determined from microelectrode impalements. Open circles indicate positions of the four poles of the extracellular recording electrode, and the star indicates the barrier around which impulses spread to produce the downward and subsequent upward activation shown by the vector loop in Figure 7A. Panel B: Plot of vector angle versus time for the vector loop shown in Figure 7.

and vector loop. Action potential AP1 depolarized during component loop 1 of the vector in A; AP2 and AP3, during vector component 2; and AP4, during vector component 3. Characteristics of the action potentials are essentially normal. Figure 8 shows correlation of local activation directions at different times with the direction of the vector loop. Conduction velocity from right to left across the tissue is approximately 0.2 m/sec but is irregular. The thick arrows indicate directions of impulse spread around these anatomic barriers determined from microelectrode impalements.
Panel B presents a plot of vector angle versus time for the vector loop shown in Figure 7, which also corresponds to the microelectrode map shown in panel A. The approximate position of the four poles of the vector probe electrode are shown by circles in panel A. Separate components of the vector loop correspond to different directions of activation in the microelectrode impalement map. The electrograms contain little amplitude up to between 20 and 25 msec. From 25 to approximately 31 msec, vector angles are pointing between -170° and +140° indicating essentially right-to-left impulse spread before the first area of anatomic barriers are encountered. This corresponds to the region between microelectrode impalements having activation times of 19-29 msec. From approximately 32 to 36 msec, activation is proceeding leftward and downward. Impulses proceeded downward, around the anatomic barrier from the activation in time indicated by 29 msec toward that indicated by 34-35 msec lower down. After activation proceeds around this anatomic barrier, it courses superiorly as indicated in the microelectrode map at activation times between 34 and 40 msec. This corresponds to a vector direction of approximately +90°. Finally, impulses appear to be proceeding in both directions around the anatomic barrier labeled by a star so that a collision occurs. From 40- to 47-msec impulses are proceeding leftward and downward near the area of the probe around the anatomic barrier labeled by the star. This corresponds to the last component of the vector loop at approximately 43 msec located from -60 to -120 degrees.

In one of the seven areas displaying multidirectional vector loops, microelectrode impalements correlated with only one of the major directions of activation seen in the extracellular vector loop. In this case, no obvious region that could not be impaled was identified. The “missing” direction of activation may have represented activation deep to the area reached by microelectrode impalements.

Experiments In Vivo

A total of 160 sites from 10 animals in areas of experimental myocardial infarction were analyzed. Mean electrogram amplitude was 8.0±6.4 mV, and mean electrogram duration was 24.9±11 msec. Sixty-seven percent of the electrograms recorded were classified as abnormal (amplitude less than 6 mV, duration greater than 128 msec, or a ratio less than 0.28) by previously defined criteria. Nineteen of 150 sites (13%) had two or more instantaneous vector directions of activation more than 90° apart. Multidirectional vectors were only recorded from abnormal sites, and thus, 19 of the 100 (19%) abnormal sites had multidirectional vectors.

To gain insight into how the direction of activation affects the local conduction patterns, we analyzed local electrograms in vector loops at 11 individual markedly abnormal sites when pacing from 6 mm away from the recording site at four sides surrounding the recording site, each 90° apart (protocol B). Mean electrogram amplitude was 6.8±4.6 mV, and mean electrogram duration was 38.0±10.9 msec. The mean ratio was 0.22±0.24. Forty-one of 44 recordings (four recordings at each of the sites) contained at least one abnormal electrogram. At all sites, at least three of the four recordings contained abnormal electrograms. The direction from which one of these areas was activated markedly affected the number of components in a multidirectional vector loop. In only two of the 11 sites was the same number of components of the vector loop identified regardless of pacing direction. An example of one of these sites activated from all four directions is shown in Figure 9. This figure shows an example of bipolar electrograms and vector loops recorded at a single site, when that area is activated from four different directions. In this example, the recording probe was approximately 7 mm from the pacing electrode. Note that electrogram morphology and characteristics of the vector loop differ depending on the pacing site. In particular, whereas panels B and C show clearly divergent directions of activation, panel D shows only one major direction. In addition, note that whatever the pacing direction, there is a leftward, upward component present in the vector loop. Of the 44 vector loops analyzed (11 sites, 4 loops at each site), 22 vector loops demonstrated one major activation direction; 20 vector loops, two activation directions; and two vector loops, three activation directions. When examining the electrograms, there was a mean difference of 5.9 mV in amplitude between any of the four pacing directions at the same site and a mean difference of 19.1 msec in duration. The coefficient of variation was 27% in amplitude and 22% in duration.

Discussion

There are two major findings from this study. First, instantaneous components of vector loops formed by summing orthogonally recorded electrograms were shown to accurately reflect the direction of activation in infarcted myocardium. Thus, the vector technique may help elucidate complex activation patterns in areas where abnormal extracellular electrograms are recorded in which discrete activation times may be difficult to identify such as in areas of fractionated electrograms where multiple peaks are present. Second, two discrete patterns of activation were identified in vivo in experimental myocardial infarction. In one pattern, slow and presumably discontinuous conduction was present with the major activation wave fronts all proceeding in one direction. This pattern was present in 81% of sites with abnormal electrograms. In the remaining 19% of sites, two major separate vector loop directions were identified. This suggests within a local area that at least two wave fronts separated by an anatomic or functional barrier exist with conduction proceeding in two different directions.
Instantaneous Vectors

Previous work from our laboratory has demonstrated that the maximum X-Y amplitude of the vector loop created by summing orthogonally placed bipolar electrograms represents the direction of activation in cardiac tissue. A potential advantage of the technique is that the direction of cardiac activation can be determined while recording at only one probe site. In our previous report, we demonstrated that vector loops recorded from abnormal infarcted areas had notched and multiple components, and in some situations those multiple components were activated in different directions. We postulated that instantaneous vectors comprising individual components of these vector loops would represent local activation directions occurring at different times within the recording field of the probe electrode. Such different activation directions and times might be present because anatomic barriers (which might be physiological, such as blood vessels, or pathological, such as areas of fibrosis in healed myocardial infarction) would electrically isolate groups of cells in the local area and cause them to be activated in different directions. This hypothesis has been validated in the series of experiments performed in vitro in tissues removed from experimental myocardial infarction.

Electrode Field of View

A crucial question in analyzing activation information obtained from any extracellular recording technique is the area of tissue that the recording technique reflects. We have previously suggested that at least in vivo the vector probe with a 2-mm interelectrode distance records from approximately an area of 5 mm in diameter. These calculations suggested a "field of view" for the recording electrode of between 2 and 3 mm. The smaller distance compared with what we have previously described in vivo may be due to differences in current distribution in vitro and in vivo. This could decrease the lateral spread of current and, thus, field of view of the electrode.

Propagation in Experimental Myocardial Infarction

Microelectrode impalements in areas of myocardial infarction revealed results similar to those that have been previously reported. In these preparations, which were from myocardial infarction of more than 1 week, action potential amplitude and peak dV/dt were similar to those in normal epicardial tissue. Spear et al have demonstrated that although abnormalities of the upstroke of the action potential and of action potential amplitude may be present 3–5 days after occlusion-reperfusion experimental myocardial infarction, these action potential parameters have, by and large, returned to normal by 8–15 days after the procedure. Other investigators have described similar findings. Slow conduction in these infarcted regions may be due to problems in cell-to-cell coupling. Gardner et al also found that abnormal and fractionated electrograms could be recorded from areas of healed experimental myocardial infarction in vitro depending on the presence of normal intracellular action potentials. Using electrophysiological and histological techniques, they provided evidence that the ingrowth
Directionally Dependent Activation in Experimental Myocardial Infarction

We found that the most common pattern of activation in relatively local areas of epicardium containing slow conduction is slow discontinuous conduction proceeding in one major activation direction. Small numbers of cells and side branches activated in different directions may also be present. However, in 19% of cases analyzed, a vector loop containing two major components with different directions of activation was identified in vivo. Such loops were similar in gross morphological characteristics to those recorded in vitro in which the different directions of activation were confirmed by isochronal mapping by microelectrode impalements. Several investigators have demonstrated that at least in experimental myocardial infarction, intramural microreentrant circuits may be present in a relatively localized area forming the anatomic and electrophysiological substrate for ventricular tachycardia. Although we did not correlate activation patterns with arrhythmias in this study, it is possible that the multidirectional activation found in certain areas indicates a degree of longitudinal dissociation that may facilitate the development of reentrant arrhythmias.

Conduction Patterns in Experimental Myocardial Infarction In Vivo

One characteristic of uniform anisotropic tissue is that activation of the same area from directions 180° apart is similar and uniform. Spach et al. have demonstrated that even noninfarcted nonuniformly anisotropic tissue such as that present in the atrium may be activated differently when going from left to right versus from right to left across the same area of tissue. Similar differences in activation have been found at Purkinje muscle junctions and in an isthmus of tissue simulating the Wolff-Parkinson-White syndrome. Such differences in activation may be due to fiber branching, angulated cell-to-cell connections, or different sizes of proximal and distal current sinks. Directional differences in activation have been anecdotally noted in experimental myocardial infarction but have not been carefully characterized. We have confirmed in vivo that gross characteristics of epicardial electrograms differ depending on the direction of activation. Significant differences in electrogram amplitude and duration were seen even when the same area of tissue was being activated left to right versus right to left. In addition, the geometric pattern of activation appeared to vary depending on pacing direction. The number of components of vector loops with distinct activation directions differed depending on pacing site. There were only two of 11 cases in which the same number of distinct directional components was present regardless of the pacing site.
Limitations

There are several limitations to the current study. As with any surface technique, two-dimensional vector loops are unable to account for intramural myocardial activity that may be important in conduction in vivo. Thus, the contribution of intramural activation to propagation could not be defined in the in vivo experiments, and further work including intramural recordings and potentially three-dimensional vectors will be required to completely elucidate activation in the intact heart. However, since some useful information can be gained from epicardial activation patterns and since a three-dimensional in vitro validation study was not feasible, two-dimensional vectors were used in this study. In addition, the resolution of myocardial activation in this study was not infinite. Major deflections in vector loops were analyzed and validated in vitro, but smaller notches and irregularities were not addressed. Finally, only experimental infarctions up to 3 weeks old were studied. It is possible that multidirectional vectors would be more common in older infarctions.

In summary, vector techniques may be useful in characterizing the details of complex conduction occurring in experimental myocardial infarction. Microscopic and macroscopic discontinuities are present, which create disordered local conduction and produce differing activation directions in small areas of surviving myocardium. Further work will be needed to demonstrate which characteristics of local conduction provide the anatomic substrate necessary for the development of reentrant arrhythmias.

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References


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