Functional Role of the Epicardium in Postinfarction Ventricular Tachycardia

Observations Derived From Computerized Epicardial Activation Mapping, Entrainment, and Epicardial Laser Photoablation

Laszlo Littmann, MD; Robert H. Svenson, MD; John J. Gallagher, MD; Jay G. Selle, MD; Samuel H. Zimmern, MD; John M. Fedor, MD; and Paul G. Colavita, MD

Background. Conventionally, monomorphic sustained ventricular tachycardia in patients with remote myocardial infarction is believed to originate from the subendocardium. In a previous study, we demonstrated that electrical activation patterns during ventricular tachycardia occasionally suggest a subepicardial rather than subendocardial reentry.

Methods and Results. This study prospectively evaluated the functional role of the epicardium in postinfarction ventricular tachycardia with complex intraoperative techniques including computerized electrical activation mapping, entrainment, observation of changes in activation pattern during successful epicardial laser photoablation, and histological study. Five of 10 consecutive patients undergoing intraoperative computerized activation mapping had 10 ventricular tachycardia morphologies displaying epicardial diastolic activation. These 10 "epicardial" ventricular tachycardias revealed the following global activation patterns: monoregional spread (two), figure-eight activation (five), and circular macroreentry (three). Entrainment of ventricular tachycardia using epicardial stimulation was successfully performed from an area of slow diastolic conduction in four tachycardia morphologies. During entrainment, global activation remained undisturbed with recordings showing a long stimulus to QRS interval, unchanged QRS morphology, and pacing capture of all components of the reentry circuit. Neodymium:yttrium aluminum garnet laser photoablation was delivered during ventricular tachycardia to epicardial sites of presumed reentry. Epicardial photoablation terminated five of five figure-eight tachycardias, two of three circular macroreentry tachycardias but not the monoregional tachycardias. Electrophysiological recordings during epicardial laser photoablation demonstrated progressive prolongation of ventricular tachycardia cycle length and apparent interruption of the presumed reentrant circuit. Histological evaluation of the reentrant region (three patients) showed a rim of surviving myocardium under the epicardial surface.

Conclusions. This study suggests that 1) chronic postinfarction ventricular tachycardia may result from subepicardial macroreentry, 2) slow conduction within the reentry circuit can be localized by computerized mapping and epicardial entrainment, and 3) ventricular tachycardia interruption by laser photoablation results from conduction delay and block within critical elements of the reentrant pathway. Viable subepicardial muscle fibers may constitute the underlying pathology. (Circulation 1991;83:1577–1591)

Monomorphic sustained ventricular tachycardia in patients with remote myocardial infarction is generally believed to be due to reentry. The consensus is that in the vast majority of cases the anatomic-electrophysiological substrate of the arrhythmia is located in the suben...
TABLE 1.  Patient Characteristics

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<th>Aneurysm</th>
<th>Preop ejection fraction</th>
<th>VT morphologies (n)</th>
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MI, myocardial infarction; Preop, preoperative; Intraop, intraoperative; VT, ventricular tachycardia; M, male; LAD, left anterior descending coronary artery.

docardium,5–8 and surgical and transcatheter techniques have been devised to remove or ablate this endocardial focus.9–19 Recently, we showed that during intraoperative electrical activation mapping of postinfarction ventricular tachycardia, electrophysiological phenomena that are usually considered to be markers of the “site of origin” of ventricular tachycardia can be recorded from the epicardial surface in a number of patients.20,21 Epicardial neodymium: yttrium aluminum garnet (Nd:YAG) laser photocoagulation of these areas has successfully cured the arrhythmias.20,21 The purpose of the present study was to prospectively evaluate the functional role of the epicardium in postinfarction ventricular tachycardia with more sophisticated intraoperative electrophysiological techniques including computerized mapping of global electrical activation, entrainment of ventricular tachycardia from the presumed epicardial site of origin, and observation of the changes in activation pattern during successful laser photoablation from the epicardial surface. In a few patients, histological studies were also performed to identify the underlying pathology.

Methods

Patient Characteristics

From October 1988 to October 1989, 10 patients with drug-resistant ventricular tachycardia associated with a previous myocardial infarction underwent intraoperative computerized epicardial activation mapping of 25 different ventricular tachycardia morphologies induced during surgery. Five patients had anterior infarctions, and five patients had inferior infarctions. Left ventricular aneurysm was present in six patients. The mean (±SD) preoperative ejection fraction was 0.38±0.11 (range, 0.21–0.50). All patients underwent Nd:YAG laser photocoagulation of the ventricular tachycardia site of origin. Details of our FDA-approved protocol have been previously described.22 There was one postoperative death (10%) related to low cardiac output. Nine patients were followed up by serial electrophysiological testing. Five of the nine survivors had at least one and a total of 10 ventricular tachycardia morphologies during surgery that showed diastolic activation over the epicardium. In eight of 10, the entire diastolic interval was represented by epicardial electrograms. The total number of ventricular tachycardias (epicardial or endocardial) observed before and induced during surgery in the five patients who had at least one “epicardial” ventricular tachycardia were eight and 13, respectively (Tables 1 and 2). The present report summarizes our intraoperative electrophysiological observations in 10 epicardial ventricular tachycardias.

Intraoperative Electrophysiological Evaluation of the Epicardial Surface

Intraoperative epicardial activation mapping during sinus rhythm23 and during ventricular tachycardia24 was performed by a commercially available computerized mapping system (Bard Electrophysiology, Billerica, Mass.). A flexible sock array with 56 evenly distributed bipolar button electrodes was pulled over the surface of the ventricles under normothermic conditions. Distances between adjacent electrodes varied from 8 to 25 mm. Fifty-six bipolar electrograms together with seven surface electrocardiographic leads were connected to a 64-channel amplifier. A computer program automatically identified the points of maximal amplitude and computed their timing to a preset reference line. The reference point was always the onset of the QRS complex as identified from the surface electrocardiographic leads. The diastolic interval was defined as the time interval from the end of one QRS complex to the onset of the following QRS complex in the surface leads. Activation timing of local electrograms in the last two thirds of the diastolic intervals were displayed as negative values measured back from the reference line closing the diastolic interval. All other electrograms were timed to the right of the reference line and were displayed as positive values. Whenever split potentials or continuous electrical activity was observed during ventricular tachycardia, the activation time marker was manually set at the first sharp component of the local electrogram. The computer software could also identify maximum slopes of individual electrograms. Activation markers were omitted whenever timing of local electrograms remained doubtful even after scanning several consecutive cycles. During sinus rhythm, an area of late potentials extending beyond the termination of the QRS com-
plex was identified. Ventricular tachycardia was initiated by burst pacing or premature stimulation through a bipolar plaque electrode sewn on the ventricular surface or by pacing through a hand-held bipolar probe. Epicardial activation maps of individual ventricular tachycardia morphologies, and occasionally also of the initiating paced beat, were acquired. In five ventricular tachycardia morphologies, "entainment" of the ventricular tachycardia from a site displaying mid-diastolic activation during ventricular tachycardia was attempted by pacing the appropriate sites over the epicardium through openings of the sock electrode. Paceing was performed at a rate slightly faster than the ventricular tachycardia rate by a hand-held probe. Epicardial activation maps of the last entrained beat and the first tachycardia beat after release of pacing were obtained and analyzed. Details of the procedure are described in "Results."

Epicardial electrical activation maps were displayed in a polar view (Figure 1), and anatomic landmarks were referenced to the computer-generated maps. For the purpose of this publication, the original color maps were accurately redrawn in black and white. The electrograms displayed in the illustrations are photocopies of the original computer-generated recordings.

**Epicardial Laser Photocoagulation**

The laser source was a continuous wave Nd:YAG laser (MediLas II, MBB Medizintechnik, Munich, FRG) coupled to a 600-μm core diameter gas-cooled silica quartz fiber. Laser power at the tip of the fiber was set at 50–80 W. Irradiating spot size was 0.5–1.0 cm. Details of the laser procedure were previously described. Laser photoablation was initially performed at epicardial sites showing mid-diastolic activation during ventricular tachycardia. The area of laser irradiation was gradually extended in a circular fashion until the ventricular tachycardia was terminated. During laser termination of ventricular tachycardia, an attempt was made to observe the effects of lasing on the presumed reentrant circuit by keeping a mapping probe on an epicardial site showing diastolic activation. In the last two patients and three ventricular tachycardia morphologies, lasing was performed with the sock electrode array being kept on the surface of the heart, allowing acquisition of global activation maps during laser photoablation-induced termination of the ventricular tachycardia. In three patients, epicardial laser photocoagulation successfully terminated ventricular tachycardia before ventriculotomy. In two patients, epicardial lasing was performed after ventriculotomy after an unsuccessful attempt at photoablation from the endocardium; such an approach precludes the use of the sock electrode during lasing. Myocardial segments from areas showing diastolic activation during ventricular tachycardia were obtained for histological evaluation in three patients.
MONOREGIONAL SPREAD

Figure 2. Activation map of monoregional spread of epicardial activation during ventricular tachycardia. Shaded area on the top represents presystolic activity. Ventricular depolarization (dotted lines) circumscribes an area of scar tissue (shaded area in middle). Slow conduction late in systole moves in the direction of the presystolic activity. No temporal continuity, however, occurs between the late and early activation sites over the epicardium. LAD, left anterior descending coronary artery. Isochrones computed from timing of local epicardial electrograms are expressed in milliseconds.

Clinical Follow-up

Electrophysiological testing of ventricular tachycardia inducibility was performed before hospital discharge and 3–6 months after laser arrhythmia surgery. Programmed stimulation was performed from two right ventricular sites at two basic cycle lengths with three premature impulses, and incremental burst pacing was also applied.21,22

Results

Patterns of Epicardial Activation

According to definition, all 10 ventricular tachycardia morphologies analyzed in this study displayed epicardial activation points in the diastolic interval. Three basic patterns of epicardial activation were identified from the computer-generated maps (Table 2). Two ventricular tachycardias showed a “monoregional” spread of epicardial activation.7,29 In the monoregional pattern, presystolic electrograms were recorded over a circumscribed area of the epicardial surface, and spread of epicardial activation was radial from this area. In one case, systolic activation seemed to proceed around and circumvent an area of visible scar tissue (Figure 2), but a continuum of diastolic activity over the epicardial surface could not be identified. Five ventricular tachycardia morphologies displayed a figure-eight activation pattern over the epicardial surface.29–32 Criteria for establishing figure-eight activation included each of the following observations: 1) A sequence of local epicardial electrograms had to span the entire diastolic interval as viewed from the surface electrocardiographic leads, from the end of one QRS complex to the beginning of the next QRS complex. 2) Electrical activation in diastole had to proceed over a narrow path bracketed by two arcs of conduction block from either side. Presystolic activation, that is, local electrograms in the last 50 msec of the diastolic interval, usually fanned out from the head of the narrow path of pandiastolic activation. 3) The systolic component of ventricular activation had to reenter the tail end of the diastolic pathway by circulating around both arcs of the functional conduction block, thus establishing the two circular portions of the figure-eight pattern. 4) Temporal and spatial continuity between the late systolic components and early diastolic components of the presumed reentrant circuits had to be present. Figure 3A depicts the epicardial activation map of a ventricular tachycardia fulfilling all the above criteria of the figure-eight pattern. Figure 3, panels B–D show representative electrogram sequences spanning the diastolic and systolic intervals. In all five figure-eight ventricular tachycardias, the pandiastolic path was located close to the margin of a left ventricular aneurysm or along the edge of visible scar tissue. In several ventricular tachycardia morphologies, certain low-amplitude bipolar electrograms in the slow diastolic pathway had to be omitted from the analysis. Nevertheless, an adequate number of activation points were present in each case to allow for tracing the pandiastolic impulse. The length of the diastolic path was roughly estimated in each case by measuring the distance from the button electrode representing the earliest electrogram in the diastolic interval to the button electrode associated with activation at the onset of the QRS complex representing zero activation timing, that is, from the tail to the head of the diastolic path. Overall conduction velocities in the diastolic pathways were approximated by dividing the pathway lengths by the conduction times within the paths. The mean (±SD) diastolic conduction velocity in the five figure-eight cases was thus estimated to be 0.88±0.33 m/sec. Certain portions of the diastolic path, however, had conduction velocities in the 0.1-m/sec range. Circular macroreentry was identified in three ventricular tachycardia morphologies.7,29,31–33 This vortex or ring pattern of activation was diagnosed whenever 1) a sequence of epicardial electrograms spanned the entire diastolic interval, 2) two functional arcs of conduction block bracketing a narrow path of diastolic activation were not present, therefore preventing systolic activation from proceeding in two opposite directions, and 3) temporal and spatial continuity between the late systolic components and early diastolic components of the presumed reentrant circuit was identified. In one case, ventricular activation circulated around a vortex located close to the apex of the left ventricle (Figure 4). In two ventricular tachycardia morphologies, ventricular activation both in diastole and in systole seemed to circulate around the circumference of a left ventricular aneurysm (Figure 5). Overall conduction velocities over the entire diastolic pathway in the
three circular macroreentrant tachycardias measured 0.69±0.16 m/sec, with certain segments of diastolic activation displaying much slower conduction.

Attempted Entrainment From the Presumed Epicardial Site of Origin

Entrainment of the ventricular tachycardia from the presumed epicardial site of origin was attempted in five ventricular tachycardia morphologies in three patients (Table 2).34–37 Three tachycardias had a circular pattern, and two tachycardias had figure-eight patterns. Epicardial stimulation with a hand-held bipolar probe electrode was initiated at a rate slightly faster than the ventricular tachycardia rate. The initial site of stimulation was at the area displaying middiastolic activation. The pacing probe was then moved to adjacent areas until the paced QRS morphology became identical to the ventricular tachycardia morphology.34–37 For obvious clinical reasons, only a limited number of pacing sites were tested, and only one to three pacing cycle lengths were used in individual cases. The results of the entrainment studies, therefore, do not represent a thorough analysis of the responses to pacing from all areas within the diastolic path.

Global epicardial activation maps were obtained on the last entrained beats and on the first ventricular tachycardia beats after release of epicardial stimulation. The timing and morphological characteristics of individual electrograms were also analyzed. In four ventricular tachycardia morphologies, “exact” epicardial entrainment was achieved.34,37 Exact entrainment was characterized by the following observations: 1) The stimulated beats and spontaneous tachycardia beats had identical or near-identical QRS morphologies in all surface electrocardiographic leads. 2) Global epicardial activation was identical for the entrained beat and the spontaneous tachycardia beat in the computer-generated maps. 3) Termination of pacing was followed by immediate reappearance of the ventricular tachycardia at its own intrinsic rate, morphology, and global epicardial activation pattern. 4) The stimulus to QRS intervals equaled or were greater than 100 msec in each case. Figure 4 is a representative example. In this circular macroreentrant tachycardia, pandiastolic activation was observed to extend from the anterior surface of the base of the left ventricle toward the anterior and lateral surfaces of the base of the right ventricle (Figure 4A). Ventricular tachycardia cycle length was 440 msec; QRS duration was 200 msec; and the diastolic interval measured 240 msec. The first half of the diastolic interval (shown as positive values in Figure 4A) was represented by local epicardial electrograms extending from C5 to the B1 site. The second half of the diastolic interval (shown as negative values and shaded area in Figure 4A) extended from B1 to F1. Almost the entire 440-msec cycle length had epicardial electrical representation. Middiastolic activation was observed at −100 msec to the right of the origin of the left anterior descending coronary artery. Pacing from this site during ventric-
FIGURE 4. Activation maps, electrocardiograms, and electrograms depicting epicardial entrainment of a circular macroreentry ventricular tachycardia. Panel A: Global epicardial activation during ventricular tachycardia. Panel B: Epicardial activation during epicardial entrainment. Isochrone lines are 15 msec apart. Diastolic activation is represented by shaded areas and broken lines. Systolic activation is represented by dotted lines. Pacing site is close to an area displaying middiastolic potentials (−95 to −80 msec) during ventricular tachycardia. Short arrows depict the antidromic wave front. Panel C: Surface electrocardiogram at the time of cessation of pacing. Stimulus-to-QRS interval is 100 msec. Panel D: Epicardial electrograms from the presumed reentrant region during release of overdrive pacing. Perfect or near-perfect match of global epicardial activation and surface electrocardiographic morphology occurs between entrained and nonentrained beats. Cessation of pacing is followed by an immediate resumption of ventricular tachycardia at its own intrinsic rate. This results from the last circulating impulse, which is not preempted by a paced complex. Isochrones computed from timing of local epicardial electrograms are expressed in milliseconds. St, stimulus artifacts; ECG, electrocardiogram; CL, cycle length; C, left lateral chest lead. See text for further details.
Epicardial tachycardia at a cycle length of 360 msec resulted in a global activation pattern identical to the ventricular tachycardia activation pattern (Figure 4B) and in a near-perfect QRS match on the entrained and nonentrained beats (Figure 4C). Again, almost the entire 360-msec cycle length had either diastolic or systolic epicardial representation. The stimulus to QRS intervals during pacing measured 100 msec, identical to the local electrogram to onset of QRS intervals during the spontaneous tachycardia. Figure 4D illustrates representative epicardial electrograms from the presumed reentrant region during cessation of the epicardial entrainment. The activation sites are referenced to the activation map in panel A. The smaller thin arrows represent presystolic wave fronts extending from the pacing site between areas B1 and G1 to the onset of ventricular activation in the electrocardiogram that is simultaneous with epicardial activation at F1. The longer heavy arrows represent orthodromic activation at the most distal end of the circuit, in the slow conduction zone responsible for middiastolic activation during ventricular tachycardia. All electrogram configurations in front of and distant from the pacing site were identical during entrainment and after cessation of pacing. Two epicardial sites behind the paced area, namely, areas C1 and B1, however, had paced electrogram contours that were different from those during the un paced tachycardia. During entrainment, C1 site was activated by the orthodromic wave front from the pacing impulse because the electrogram preceding the first tachycardia beat after

**Figure 5.** Activation maps, electrocardiograms, and electrograms depicting epicardial entrainment of a macroreentrant tachycardia from close to the exit site of a slow conducting diastolic pathway. Panel A: Delayed potentials over an aneurysmal surface during sinus rhythm. Panel B: Epicardial activation map during ventricular tachycardia. Shaded area and broken line represent slow diastolic activation; dotted line represents systolic activation. Panel C: Epicardial activation map of an entrained beat. Epicardial stimulation was performed from behind the B5 electrode displaying presystolic potentials during ventricular tachycardia. Panel D: Identical surface QRS morphologies during entrainment and after cessation of pacing. Panel E: After release of pacing, epicardial activation sequence and epicardial electrogram morphologies over the reentrant area remained unchanged. Panel F: Perfect match in presystolic epicardial electrogram morphology and an identical temporal relation to ensuing QRS complexes on the last entrained and first nonentrained beats. Origin of the second component of the local electrogram at B5 is uncertain. Stimulus-to-QRS intervals are long at 120 msec. Isochrones computed from timing of local epicardial electrograms are expressed in milliseconds. LAD, left anterior descending coronary artery; St, stimulus artifacts; ECG, electrocardiogram; C, left lateral chest lead.
cessation of pacing occurred with the same morphology as the preceding electrograms during pacing (Figure 4D). The different morphology of the electrogram at this site during entrainment from that during spontaneous tachycardia might have been due to a slight alteration in the activation sequence around the C1 site during entrainment because of the increase in rate. On the other hand, the B1 site was activated by the antidromic wave front from the pacing impulse because it showed completely different electrogram morphology during pacing from that during the spontaneous tachycardia, and furthermore, the first electrogram after cessation of pacing occurred at an interval different from the pacing cycle length. The collision site of the antidromic wave front and the orthodromic wave front originating from the previous pacing impulse was, therefore, between the C1 and B1 sites, as indicated in Figure 4B. Release of pacing was followed by immediate resumption of the ventricular tachycardia resulting from slow pandiastolic activation over epicardial regions represented in the global activation maps. Figure 5 is another example of exact entrainment. Panel A shows a sinus map with delayed epicardial activation over a left ventricular aneurysmal surface. Panel B is the computer map of a ventricular tachycardia beat. Ventricular tachycardia cycle length was 360 msec, and the diastolic interval measured 230 msec. Diastolic activation was observed at the margin of the left ventricular aneurysm. The second half of the diastolic interval was not fully represented by epicardial activation sites. In this case, exact entrainment was achieved by epicardial overdrive pacing at a cycle length of 320 msec from an area closer to the head of the diastolic path (Figure 5C). Global epicardial activation during pacing was practically identical to epicardial activation during ventricular tachycardia, a fact also reflected in perfectly identical QRS morphologies on the entrained and nonentrained beats (Figure 5D). The sequence and morphology of the epicardial electrograms in the region of reentry were also identical between the paced and spontaneous tachycardia beats (Figure 5E). Figure 5F shows a surface electrocardiographic lead and presystolic local epicardial electrograms of the last two entrained beats and the first ventricular tachycardia beat at the time of cessation of pacing. The findings reflect the fact that pacing was performed from a site orthodromically proximal to the recorded presystolic electrogram as indicated in Panel C. Stimulation from this area resulted in several phenomena suggesting a pacing capture of a portion of the slow diastolic conduction pathway over the epicardium: 1) The ventricular tachycardia rate accelerated to the pacing rate; 2) a local presystolic epicardial electrogram was advanced by the pacing impulse; 3) morphology of the entrained electrogram was identical to the morphology of the presystolic electrogram of the spontaneous ventricular tachycardia beat and; 4) timing of the presystolic electrogram to the corresponding QRS complex was also comparable on the entrained and nonentrained beats.

Observations During Successful Epicardial Laser Photoablation

Nd:YAG laser photoablation was delivered during ventricular tachycardia to epicardial sites of presumed reentry as suggested by the global activation pattern, region of slow diastolic conduction, and sites of perfect entrainment. Epicardial laser photoablation successfully terminated all five figure-eight ventricular tachycardias and two of three circular macroreentry tachycardias but not the monorregional tachycardias (Table 2). In one circular macroreentrant case (patient 4) epicardial fat overlying the area of middiastolic activation precluded effective photocoagulation. In this patient, cryoablation of the epicardial and opposing endocardial surfaces was used. In each successful case, epicardial lasing at the site of diastolic activation resulted in a progressive prolongation of the ventricular tachycardia cycle length followed by termination of the ventricular tachycardia. Apparent interruption of the presumed reentrant circuit coinciding with tachycardia termination was documented in four cases. Figure 6 is an example. The tachycardia is the one represented in Figure 3. Epicardial laser photoablation was performed at an area showing middiastolic activation within the slow conducting diastolic path, and the mapping probe was positioned in the immediate vicinity of this area, distal to the lasing site along the diastolic activation pathway. Before initiation of laser photoablation, the time interval between the onset of the QRS complex preceding the local electrogram to the first sharp component of the bipolar electrogram (QRS-BE interval in Figure 6) measured 225 msec, whereas the local electrogram preceded the following QRS complex by 85 msec (BE-QRS interval in Figure 6). Epicardial laser photoablation resulted in termination of the ventricular tachycardia within 13 seconds. During lasing, the following electrocardiographic changes were observed: 1) Ventricular tachycardia cycle length gradually increased; 2) increase in cycle length resulted from a gradual prolongation in the QRS-BE intervals from 225 to 315 msec; 3) BE-QRS intervals remained essentially unchanged; 4) amplitudes on the local diastolic electrograms gradually diminished; 5) termination of ventricular tachycardia coincided with disappearance of the local diastolic electrogram; and 6) local epicardial activation reappeared in the form of a delayed potential on the first supraventricular beat after ventricular tachycardia termination (Figure 6B). These observations can be best explained by a laser photoablation-induced gradual conduction prolongation and eventual conduction block in the first half of a slow conducting macroreentrant pathway responsible for the ventricular tachycardia. Figure 7 is another example of laser-induced ventricular tachycardia termination. Panel A shows anatomic landmarks and both the diastolic and systolic paths of a...
figure-eight epicardial activation. Epicardial laser photoocoagulation was performed through the sock array at an area displaying middiastolic activation, as indicated in panel B. During lasing, the ventricular tachycardia gradually decelerated. Prolongation in cycle length resulted from progressive temporal separation of diastolic electrograms situated on two sides of the lased region (panel B). Systolic activation remained unchanged. Panel C presents bipolar electrograms along the diastolic pathway on the last three ventricular tachycardia beats before termination. Panels D–F represent diastolic electrograms at a faster paper speed. Laser photoocoagulation was performed between the A7 and G4 electrodes of the sock array. Laser photoocoagulation between sites A7 and G4 resulted in progressive prolongation of conduction time between these areas, progressive prolongation of ventricular tachycardia cycle length, and eventual termination of the ventricular tachycardia coinciding with development of conduction block between the areas in front of and behind the site of photoocoagulation.

**Histology**

In patients 2, 3, and 5, segments of the border zone of left ventricular aneurysm and normal myocardium
were harvested for histological evaluation. In all three patients, several areas showed surviving myocardial fibers in the subepicardial layer, along the outside surface of the aneurysmal wall. Strands of muscle bundles were separated by connective tissue in samples from all three patients, whereas more isolated myocardial fibers were also embedded within the epicardial fat in one patient (Figure 8). In two patients, a few surviving muscle bundles were also found closer to the inside surface of the aneurysm.

Long-term Clinical Results

A minimum of one postoperative ventricular tachycardia induction study was performed in each patient 3–36 weeks after the laser procedure. Mean clinical follow-up time was 12 months (range, 6–18 months). All four patients who had intraoperative termination of ventricular tachycardia with epicardial laser photoablation remained free of symptoms and of spontaneously occurring ventricular tachycardias. Ventricular arrhythmias could not be induced in any of these patients with our aggressive pacing protocol. In one patient (patient 4), ventricular tachycardia was induced during the postoperative electrophysiological testing, and an automatic cardioverter-defibrillator was, therefore, implanted. Morphology of the postoperative tachycardia was similar to the preoperative ventricular tachycardia, ventricular tachycardia number 8 (Table 2). This was the patient in whom extensive epicardial fat precluded adequate laser photoablation of the presumed reentrant region. Thermal ablation was attempted by cryosurgical techniques in the cold cardioplegic heart. This technique precluded short-term verification of treatment efficacy. In this patient, therefore, it remained uncertain whether treatment failure was due to a less-than-adequate recognition of the site of ventricular tachycardia origin.

Discussion

Current evidence suggests that monomorphic sustained ventricular tachycardia in patients with remote myocardial infarction is due to reentry, but the exact site and size of the presumed reentrant circuit are largely unknown.1–8 The results of the present study, we believe, provide the strongest proof to date suggesting that 1) macroreentry is an important mechanism in human postinfarction ventricular tachycardia, 2) the reentry circuit incorporates subepicar-
dial layers in a number of cases, and 3) global epicardial activation mapping and intraoperative electrophysiological evaluation can identify ventricular tachycardia that can be successfully terminated by epicardial laser photoablation.

**Evidence for Macroreentry**

To diagnose a macroreentrant ventricular tachycardia, one has to show that electrical activation during the entire diastolic interval bridging two QRS complexes is present over an anatomically defined area. The diastolic conduction pathway has to be functionally isolated along its length from the surrounding myocardium, and systolic activation should complete the loop by traveling around the arc or arcs of functional conduction block. Conduction time within the diastolic path needs to be sufficiently slow to allow recovery of the myocardium from the previous ventricular tachycardia complex.30,32,38

In eight of the 10 ventricular tachycardia morphologies analyzed in this report, a continuum of local diastolic electrograms spanning the time interval from the end of one QRS complex to the onset of the following QRS complex was recorded over an epicardial area. In five cases, the diastolic pathway was isolated from the surrounding myocardium by two parallel arcs of functional conduction block, giving rise to a figure-eight activation pattern.30,31 In three cases, a more simple ring pattern of activation was detected.33 In each instance, the slow diastolic pathway was located in the border zone of normal myocardium and left ventricular scar tissue and was usually adjacent to, but not identical with, the area that showed delayed potentials during sinus rhythm. This fact, together with observing a close temporal and spatial relation between the front end of diastolic activation and the onset of the next QRS complex strongly argues against the possibility that local diastolic activation merely represented slow conducting, dead-end pathways and was unrelated to the reentrant process.39

An even stronger argument for macroreentry was the observation of laser photoablation-induced gradual deceleration of ventricular tachycardia before termination. Our observations in humans were similar to the cryothermal interruption of reentrant ventricular tachycardias in dogs demonstrated by Gessman et al.40,41 and El-Sherif et al.42 In four cases, electrical events in the slow diastolic pathway were

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**FIGURE 8.** Histological sections in two patients with left ventricular aneurysm and ventricular tachycardia presumably related to subepicardial macroreentry. Panel A (patient 3) and Panel B (patient 5) show strands of surviving myocardial fibers embedded in subepicardial fat and connective tissue. Laser-induced photoablation is also evident. Panel A: Original magnification, ×25. Panel B: Original magnification, ×50. Masson's trichrome stain. Epi, epicardium; AN, aneurysmal wall; M, myocardial fibers; Endo, endocardium.
continuously monitored during lasing-induced tachycardia interruption. In each case, tachycardia deceleration resulted from a gradual prolongation of conduction time between the two edges of the lased area, and termination of ventricular tachycardia coincided with interruption of impulse transmission through the lased segment. The computer-generated maps failed to detect other changes in global epicardial activation before ventricular tachycardia termination. These observations can only be interpreted by assuming that the lased area within the narrow common diastolic pathway was in fact a critical element in a macroreentrant tachycardia loop.

Electrophysiological Characterization of the Site of Origin

Different investigators have various criteria for defining the site of origin of a ventricular tachycardia. During catheter mapping of the endocardium or epicardium, the area displaying the earliest presystolic electrical activation or the activation site coinciding with the onset of the QRS complex during ventricular tachycardia is usually considered to be the site of origin.\textsuperscript{4,6,10–12} Other investigators have taken the earliest endocardial or epicardial activation points as the site of origin, irrespective of whether local activation occurred in systole or diastole.\textsuperscript{43} Gessman et al.\textsuperscript{41} however, in a canine model of myocardial infarction demonstrated the failure of ventricular tachycardia cryotermination at epicardial sites that showed electrical activation coinciding with the onset of the QRS complex. Furthermore, Fitzgerald et al.\textsuperscript{44} recently showed that electrical shocks delivered to areas displaying presystolic potentials continuous with the main body of ventricular activation conspicuously failed to terminate the tachycardias. The introduction of new investigational ablation techniques for the treatment of drug-resistant ventricular tachycardia prompted several investigators to search for more reliable and more localized electrophysiological markers of critical areas within the reentrant circuit. Frank et al.,\textsuperscript{45} Stevenson et al.,\textsuperscript{45–47} Kay et al.,\textsuperscript{48,49} Morady et al.\textsuperscript{35} and Fontaine et al.\textsuperscript{37} recently demonstrated with endocardial catheter recording and stimulation studies that in certain cases the slow conduction zone of the tachycardia can be better localized by observing the electrocardiographic and electrophysiological responses of the ventricular tachycardia to premature or overdrive stimulation performed from the presumed site of origin. The concept of exact entrainment has been introduced to describe repeated pacing capture of the area of slow diastolic conduction during ventricular tachycardia.\textsuperscript{44,47} This type of response is characterized by pacing-induced advancement or acceleration of the ventricular tachycardia with marked conduction delay and without alteration of the ventricular activation sequence as indicated by a lack of change in the configuration of the QRS complex and endocardial electrograms distant from the stimulation site (entrainment without fusion). “Concealed entrainment” was first demonstrated by Okumura et al.\textsuperscript{50} in circus movement tachycardias using atiroventricular bypass tracts, and the concept was later expanded with pacing from a zone of slow conduction during ventricular tachycardia by Stevenson et al.,\textsuperscript{45} Frank et al.,\textsuperscript{34} Morady et al.,\textsuperscript{35} Waldo and Henthorn,\textsuperscript{36} and Fontaine et al.\textsuperscript{37} Our study extended these previous observations in that four ventricular tachycardias were successfully entrained from an epicardial site showing middiastolic activation during ventricular tachycardia. In each case, there was a perfect or near-perfect QRS match between the paced and spontaneous ventricular tachycardia complexes, and global epicardial activation also remained unchanged. Analysis of timing and morphology of epicardial diastolic electrograms during entrainment confirmed that the paced impulses had captured the slow conducting diastolic pathway, did not alter the exit point from this pathway, and thus advanced the tachycardia without changing its morphology. In three of four cases, epicardial laser photoablation right at the area of exact entrainment successfully terminated the arrhythmia within a few seconds of lasing, further confirming the critical relation between the site of exact entrainment and the site of origin of ventricular tachycardia.

Several observations in this study underscore the limited value of presystolic activation in defining the site of tachycardia origin. In all five figure-eight tachycardias, the slow conducting diastolic pathway was an anatomically narrow zone accommodating early-to-middiastolic electrograms. The head of the diastolic path, however, fanned out in each case, thereby spreading a large number of presystolic electrograms over a relatively large surface area (Figures 3 and 7). Although not tested, it is easy to believe that ablation of any single exit point from the slow conducting diastolic pathway displaying presystolic activation would have probably been insufficient to control the reentry process because the tachycardia could have exited over another, unaffected point. Another observation also suggests that presystolic activation probably reflects the exit point from a slow diastolic pathway rather than the pathway itself.\textsuperscript{41,42} In two ventricular tachycardia morphologies, there was a monoregional spread of epicardial activation with a close cluster of presystolic epicardial electrograms in the center of a radial spread of systolic activation. Laser photoablation of these “early” sites failed to terminate the tachycardias. These epicardial areas displaying presystolic activation probably reflected epicardial breakthrough of reentrant tachycardias originating from unidentified intramyocardial or subendocardial layers.

Role of the Epicardium

Epicardial reentry is a recognized mechanism of inducible ventricular tachycardia in dogs after experimental myocardial infarction\textsuperscript{30,31,38} but is not generally believed to be responsible for human ventricular tachycardia.\textsuperscript{5–15} Several lines of evidence in this
study, however, suggest that subepicardial layers are involved in a number of cases of postinfarction ventricular tachycardia. First, diastolic activation patterns that are usually considered to reflect the reentrant process4,7,24,30,31 were recorded over the epicardial surface. Second, exact entrainment was successfully performed from these epicardial areas. Third, histological study in three cases showed several bundles of surviving subepicardial muscle fibers interdigitated with fibrotic tissue at the border zone of scarred and normal myocardium, at areas that displayed epicardial diastolic activation during ventricular tachycardia. This network of surviving subepicardial myocardium probably constituted the anatomic substrate of the ventricular tachycardias. And last, epicardial laser photocoagulation successfully terminated these tachycardias.

It needs to be stressed that this research focused on characteristics of epicardial tachycardias and by no means suggests that ventricular tachycardias reside in the subepicardium in most cases. During a 1-year period covered in this study, 25 ventricular tachycardia morphologies in 10 patients were studied by computerized epicardial activation mapping, but only seven tachycardia configurations (28%) in four patients were cured on a long-term basis by epicardial laser photocoagulation. These seven tachycardias, however, would have probably remained treatment failures with a purely endocardial approach.

Limitations

From a strictly scientific point of view, there are several limitations to this study. First, the relatively low electrode density of our epicardial sock array precluded a detailed analysis of all parts of the epicardial reentrant circuits. Second, occasional electrograms in areas of slow diastolic conduction were of very low amplitude without a convincing sharp component and, therefore, had to be excluded from the analysis. This resulted in some extrapolation of isochrones in apparent areas of slow conduction. Third, an endocardial balloon array29,43 was not used; therefore, the endocardial activation pattern during the presumed epicardial reentry remained unknown. Fourth, as previously discussed, only limited epicardial entrainment studies were performed, and all aspects of epicardial entrainment in finding the critical site for ablation were not fully exposed. Nevertheless, we believe that epicardial computerized activation mapping, pacing studies during ventricular tachycardia, observation of the effects of laser photocoagulation during ventricular tachycardia, and the histological findings provide a compelling body of data for adequate characterization of the functional role of the epicardium in postinfarction ventricular tachycardia. Three-dimensional reconstruction of electric events during ventricular tachycardia using simultaneous endocardial, epicardial, and transmural recordings would further our understanding of the exact nature of these arrhythmias.

Clinical Significance

Laser photoablation of ventricular tachycardia from the epicardial surface is an attractive alternative to surgical techniques that require cardiopulmonary bypass and ventriculotomy. With adequate intraoperative electrophysiological evaluation, tachycardias amenable to epicardial laser photocoagulation can be identified, and about 25–30% of all ventricular tachycardias mapped in the operating room have the potential to be cured with such a closed heart procedure.20,21 Development of laser techniques resulting in transmural photocoagulation,51 combined with a more thorough understanding of electrophysiological phenomena observed over the epicardium during all forms of ventricular tachycardia may further increase the number of cases manageable by epicardial laser photoablation. Epicardial laser ablation could also become a complementary intervention in patients undergoing intraoperative implantation of a cardioverter-defibrillator.

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L Littmann, R H Svenson, J J Gallagher, J G Selle, S H Zimmern, J M Fedor and P G Colavita

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