Localization and mechanism of ventricular tachycardia by ice mapping 1 week after the onset of myocardial infarction in dogs

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ABSTRACT We developed a new technique of “ice mapping” to localize the site of termination of ventricular tachycardia in dogs 4 to 8 days after the onset of myocardial infarction. During programmed stimulation–induced ventricular tachycardia, the epicardium was mapped by moving an ice probe with a 1 cm tip over the infarct, lateral border, and normal areas. In 31 of 46 morphologically distinct sustained ventricular tachycardias, a specific area could be found that reproducibly terminated ventricular tachycardia. During ventricular tachycardia, bridging or late diastolic electrical activity was recorded from ice termination sites. In vitro microelectrode studies of 10 ice termination sites revealed slow conduction, but no spontaneous or triggered automaticity or delayed afterdepolarizations. Conduction slowed to complete block when the Tyrode perfusate was cooled from 37° to 27°C. We conclude that ice mapping can physiologically localize a site responsible for maintenance of ventricular tachycardia by termination of the arrhythmia, and that the presence of bridging or late diastolic electrical activity, slow conduction with cooling-induced block, and absence of spontaneous or triggered automaticity or delayed afterdepolarizations suggest that local cooling terminates ventricular tachycardia by slowing or blocking conduction in a reentrant loop.


THE SPEED OF CONDUCTION through cardiac tissue and the rate of firing of automatic foci are highly temperature dependent. Curtis and Travis1 found a direct negative linear relationship between conduction time and temperature in specialized conduction tissue in dogs. Coraboeuf and Weidmann2 found that the rate of phase 4 depolarization in Purkinje fibers is markedly slowed by cooling. We reasoned that local cooling of a small area of myocardium might terminate reentrant sustained ventricular tachycardia by slowing or blocking conduction if cooling was precisely located over the reentry loop responsible for maintenance of the arrhythmia. Alternatively, local cooling might slow or terminate automatic ventricular tachycardia if cooling was precisely applied to the abnormal automatic focus. This formulation was used to develop a new method of “ice mapping” to rapidly localize the site of maintenance of sustained ventricular tachycardia in dogs 1 week after onset of myocardial infarction. The results of ice mapping were correlated with those of in vivo electrogram mapping studies and with in vitro microelectrode data from ice termination myocardial zones.

Methods

Animal model of sustained ventricular tachycardia. Mongrel dogs weighing 20 to 30 kg were anesthetized with 30 mg/kg of sodium pentobarbital, intubated, and ventilated with room air with the use of a Harvard respirator. Under sterile operating conditions, the chest was opened by a left thoracotomy, and the left anterior descending coronary artery was dissected free from the epicardial surface at the level of the tip of the left atrial appendage, proximal to the takeoff of the major diagonal branches. The dogs were given a 15 mg/kg bolus of methylprednisolone followed in 15 min by a standard Harris two-stage left anterior descending coronary artery ligation.3 Steroids have been shown to increase the inducibility of ventricular tachycardia in dogs with experimental myocardial infarction.4, 5 The chest was closed and the dogs were allowed to recover. Four to 8 days after infarction the dogs were again anesthetized with 20 to 30 mg/kg sodium pentobarbital and the left lateral thoracotomy was repeated. A 12-lead electrocardiogram (ECG) was obtained and leads I and aVF were monitored continuously. The heart was suspended in a pericardial cradle. Bipolar silver-plunging electrodes were placed in the right ventricle. Ventricular tachycardia was induced by programmed stimulation with a Medtronic stimulator via the S1, S2, S3 extrastimulus technique during right ventricular drive pacing or by 3 to 6 beat bursts of rapid right ventricular pacing at cycle lengths of 200 to 300 msec. If ventricular tachycardia could not be induced, the dogs were given 1 to 10 mg/kg iv lidocaine by repeated 1 mg/kg
boluses and programmed stimulation was repeated; lidocaine has been shown to increase the inducibility of sustained ventricular tachycardia in dogs 1 week after the onset of myocardial infarction. Ventricular tachycardia was considered "sustained" if it was longer than 100 beats in duration. Ventricular tachycardia was considered "reproducible" or "the same" if it could be induced by programmed stimulation at least three times, with each run of ventricular tachycardia having the same rate and QRS morphology.

Technique of ice mapping. Ice probes (0°C) were made by freezing water in cylindrical tubes with 1 cm diameter tips. During programmed stimulation-induced ventricular tachycardia, ice mapping was begun after the duration of ventricular tachycardia exceeded 100 beats. The ice probe was moved over the exposed epicardial surface of the heart. The mapping strategy was first to move the ice probe circumferentially over the visible epicardial infarct borders, then circumferentially with decreasing radius over the central epicardial infarct, and then circumferentially with increasing radius over the accessible normal inferoapical and anterolateral epicardium (figure 1). During the first 33 induced ventricular tachycardias, the ice probe was continuously applied to the epicardium and moved at a steady rate of 1 to 2 mm/sec. During the last 13 ventricular tachycardias, the ice probe was moved in discrete increments and was held over each epicardial area for 10 sec. Parts of the right ventricle, posterobasal, and lateral left ventricular epicardium were not ice mapped. If ventricular tachycardia terminated, the location of the ice probe at the time of termination was noted and called an "ice termination site." Ventricular tachycardia with the same rate and QRS morphology induced a second time with immediate cooling of the now-identified ice termination site after the duration of the arrhythmia exceeded 100 beats. The time from onset of local cooling of a previously identified ice termination site to ventricular tachycardia termination was called the "ice termination time." The same ventricular tachycardia was reinduced three or more times in order to perform electrogram mapping (see below) and to determine the natural length of the arrhythmia. On completion of electrogram mapping, ice mapping of the epicardial infarct surface and its borders 2 cm from the ice termination site was performed to check the specificity of local cooling of the ice termination site in terminating ventricular tachycardia. The reproducibility of local cooling of the ice termination site in terminating ventricular tachycardia was confirmed by the requirement that cooling of the same site terminate each morphologically distinct ventricular tachycardia at least three times.

Technique of electrogram mapping. Composite bipolar electrodes (measuring 3 x 4 cm) were placed on the visibly normal inferior epicardium or lateral epicardium, and on the visibly infarcted anterior epicardium. The configuration and construction of composite bipolar electrodes has been previously described. In the last four experiments, composite electrodes constructed of cloth instead of paper tape were used to allow local cooling through the composite electrode. The ventricular tachycardia was then induced by programmed stimulation. The composite electrode located over the epicardial infarction was then moved over the infarction zone and its borders in an attempt to locate a site at which bridging diastolic or late diastolic electrical activity could be recorded. The composite electrode was also moved over known ice termination sites to determine whether diastolic electrical activity could be recorded from these sites. During sustained ventricular tachycardia, electrogram mapping was also performed with a roving bipolar electrode with 0.5 cm interelectrode distance mounted in a plexiglass probe with a 1 cm diameter tip. Mapping was performed by moving this bipolar electrode over the epicardial surface of the infarct and its borders, including the ice termination sites.

Electrograms, ECGs, and systemic arterial blood pressure (via the right femoral artery) were recorded on an Electronics for Medicine VR-12 recorder at paper speeds of 100 mm/sec with filter frequency settings of 0.1 to 100 Hz (ECG) and 30 to 100 Hz (electrogram).

Depth of cooling experiment. To determine the depth and magnitude of cooling produced by local epicardial cooling with a 1 cm tipped ice probe, a YSI No. 44202 thermistor was inserted epicardially at a depth of 0, 2 to 3, 5 to 7, and 10 to 11 cm (subendocardially), into visibly normal and visibly infarcted myocardium. Local epicardial cooling of 10 sec duration was performed with a 1 cm tipped probe held directly over the thermistor. The accuracy of the measurement was ±0.2°C.

In vitro microelectrode studies. At the termination of in vivo mapping experiments, a 5 x 5 cm area of epicardium centered over an ice termination zone was rapidly excised and placed, epicardial side up, in a tissue bath perfused by Tyrode's solution with the following millimolar composition: 137 NaCl, 12 NaHCO₃, 5.5 dextrose, 1.8 NaH₂PO₄, 0.5 MgCl₂, 2.8 CaCl₂, and 4.0 KCl bubbled with 95% oxygen and 5% CO₂. Transmembrane potentials were recorded with standard glass microelectrodes filled with 3M KCl with tip resistance of 10 to 20 megohms and with a W-P KS-700 amplifier, and were displayed on a Tektronix 565 oscilloscope and photographed with Polaroid film. Because ice termination sites were always near the visible lateral borders of the infarction, each ice termination site was located centrally in a 5 x 5 cm section of epicardium that contained a visibly normal and a visibly infarcted area. A bipolar silver wire pacing electrode was placed in the normal zone 1 cm from the visible epicardial infarct border. Multiple impalements were made from the visibly normal epicardial zone and in and within 1 cm of the ice termination zones to determine action potential amplitude, maximum diastolic potential, and action potential duration at 100% repolarization. Preparations were observed for spontaneous pacemaker activity or phase 4 depolarization. Thereafter each preparation was electrically paced at 15 beats at cycle lengths of 1500 to 300 msec (in decrements of 100 msec) and pacing was abruptly terminated to determine if delayed afterdepolarizations were present after the last paced beat; the method used has been
FIGURE 2. The experimental setup for microelectrode conduction-time studies is shown. A 5 x 5 cm section of epicardium containing a 1 to 2 cm round to oval ice termination site is pinned epicardial side up in a tissue perfusion bath perfused with Tyrode's solution. A pacemaker (pace) and microelectrodes (ME 1, 2, and 3) were positioned as shown. The ice termination sites were always located near the visible epicardial infarction border, shown diagrammatically as the transition from the visibly normal myocardium zone (clear area) to the visibly infarcted zone (stippled area). Conduction time in the normal zone was measured as the time of activation from the pacemaker to ME 1, conduction time in the border zone of the ice termination site was measured from the pacemaker to ME 2, and conduction time in the ice termination site was measured from ME 2 to 3.

previously described. Conduction times were determined in the normal epicardial zone, in the ice termination site, and in the border zone of the ice termination site (called hereafter the "border zone"). The experimental setup used to determine conduction times is shown in figure 2. A bipolar silver wire pacemaker electrode was placed in the visibly normal muscle zone. A microelectrode (ME 1) was placed 1 cm from the pacemaker in the normal muscle zone. Conduction time in the normal zone was measured as the time it took to proceed from the pacemaker to ME 1 during pacing at a drive cycle length of 600 msec at 37°C. Two microelectrodes were then placed 1 cm from the pacemaker electrode in the border zone (ME 2) and 1 cm within the ice termination site (ME 3), as shown in figure 2. Conduction time in the border zone was measured as the time it took to proceed from the pacemaker to ME 2. Conduction time in the ice termination zone was measured as the time of activation between MEs 2 and 3. Conduction-time experiments in the border and ice termination zones were performed at 37°C and were repeated after the Tyrode perfusate was cooled from 37°C to 27°C over a 30 min interval during pacing at a cycle length of 600 msec. We did not perform detailed activation mapping of the wavefront of activation in these experiments. Therefore, although conduction times and distances were measured, true conduction velocities could not be calculated.

**Statistical analysis.** Differences in cycle length between ventricular tachycardias terminated by local epicardial cooling versus those not terminated were tested for significance by unpaired t test. Differences between the natural length of each morphologically distinct ventricular tachycardia compared with its length when terminated by local cooling was tested for significance by paired t test. A chi-square test was used to determine the significance of the association of epicardial diastolic electrical activity at sites at which local cooling terminated ventricular tachycardia. Differences in action potential parameters and conduction times in normal, border, and ice termination zones were tested for significance by analysis of variance, with subgroup analysis by Newman-Keuls test. A probability level of .05 was considered significant.

**Results**

**Characteristics of ventricular tachycardia in the long-term steroid canine infarction preparation.** The outcomes in 60 dogs studied by the ventricular tachycardia ice mapping protocol are summarized in figure 3. Of the 60 dogs with left anterior descending coronary artery ligation on day 1 of the protocol, 33 survived for 4 to 8 days to undergo repeat thoracotomy and programmed stimulation and mapping studies. Twenty-eight of 33 had Q wave infarction; five of 33 had no electrocardiographic or gross pathologic evidence of infarction. Forty-six reproducible and sustained ventricular tachycardias were induced in 25 dogs, all of whom had Q wave infarction. Administration of lidocaine was re-

![FIGURE 3. Outcome in dogs entered into the ice mapping protocol.](http://circ.ahajournals.org/content/68/3/659.full)
quired to facilitate the induction of 36 of the 46 morphologically distinct sustained ventricular tachycardias. In 11 dogs sustained ventricular tachycardias of a single QRS morphology were induced, in nine those of two different QRS morphologies were induced, and in four those of three different morphologies were induced. In one dog, five morphologically distinct ventricular tachycardias were induced. The natural duration of ventricular tachycardia induced by programmed stimulation in dogs requiring lidocaine was determined in the last consecutive 13 induced arrhythmias, and was found to be 622 ± 88.6 sec (mean ± SEM). Of 46 induced sustained ventricular tachycardias, 31 could be terminated by local epicardial cooling and 15 could not. The cycle length of 31 ventricular tachycardias terminated by local epicardial cooling was 208 ± 7.9 msec (mean ± SEM). The cycle length of 15 ventricular tachycardias not terminated by local epicardial cooling was 178 ± 19.7 msec (mean ± SEM). The rates of ventricular tachycardias that were not terminated by local epicardial cooling were significantly faster than the rates of those terminated by cooling (p < .05 by unpaired t test).

Results of ice mapping studies. In 31 of 46 ventricular tachycardias, a specific ice termination site was found at which local cooling reproducibly terminated the arrhythmia at least three times. The ice termination sites measured 1 to 2 × 1 to 2 cm and were located on the visible epicardial infarction borders in all 31 instances. Ice termination sites were generally specific for each morphologically distinct ventricular tachycardia. Local cooling of other border areas, central infarct areas, or normal epicardium 2 cm from the ice termination sites did not reproducibly terminate any ventricular tachycardia. There were nine dogs with two morphologically distinct sustained and reproducible ventricular tachycardias that could be terminated by local epicardial cooling. In seven of nine dogs, each ventricular tachycardia had its own ice termination site and the two sites were separated by more than 2 cm. There was overlap of the ice termination sites in the other two dogs. In the last consecutive 13 ventricular tachycardias, the natural length of the arrhythmia was determined and found to be 622 ± 88.6 sec (mean ± SEM). For the same 13 ventricular tachycardias ice termination sites were found by ice mapping in 134 ± 20.7 sec (mean ± SEM). On reinduction of the same 13 ventricular tachycardias, immediate cooling of the previously identified ice termination sites terminated the arrhythmia in 7.7 ± 0.88 sec (mean ± SEM). Thus, local epicardial cooling significantly shortened the natural length of these 13 ventricular tachycardias (p < .01 by paired t test). Local epicardial cooling slowed the cycle lengths of these 13 ventricular tachycardias from 208 ± 7.7 msec (mean ± SEM) to 242 ± 11.2 msec just before termination (p < .001 by paired t test). Increase in cycle length just before termination occurred in 11 of 13 ventricular tachycardias, with no change in cycle length in one and a decrease in cycle length in one. The ventricular tachycardia showing a decrease in cycle length was converted to normal sinus rhythm by local epicardial cooling three times, but it also degenerated to ventricular fibrillation on two occasions after local cooling of the same site. The natural length of the first 33 induced ventricular tachycardias and the precise timing required to initially map and find an ice termination site were not determined.

In four of the last 13 ventricular tachycardias reproducibly terminated by local cooling, application of local pressure of a similar (but uncalibrated) magnitude to that used during ice mapping with exploring composite or bipolar electrodes at room temperature terminated ventricular tachycardia.

Results of electrogram mapping studies. Bridging diastolic or middle to late diastolic electrical activity could be recorded by the composite electrode from 27 ice termination sites in 31 morphologically distinct ventricular tachycardias that could be terminated by local cooling. Isoelectric diastole was recorded from the epicardium of the remaining four ice termination sites.

Examples of diastolic electrical activity recorded from ischemic zones encompassing ice termination sites during ventricular tachycardia are shown in figures 4, 5, and 6. In figure 4, ventricular tachycardia was terminated by local cooling through a composite electrode. Note the change in pattern (arrow) and increase in cycle length just before termination. This ventricular tachycardia did not terminate by pressure on the ice termination site alone. In figures 5 and 6, two morphologically distinct ventricular tachycardias were induced in the same dog. These ventricular tachycardias had their own ice termination sites, located 3 cm distant from each other. The ventricular tachycardia shown in figure 5 could be terminated only by cooling, whereas the arrhythmia in figure 6 could be terminated by either pressure or cooling. Results of termination with pressure are shown in figure 6. As in figures 4, 5, and 6, the patterns of diastolic electrical activity recorded during ventricular tachycardia were always repeated and reproducible. Local bipolar mapping of the central epicardial infarct and its visible borders was also performed with a roving bipolar electrode during ventricular tachycardia. All ice termina-
FIGURE 4. Example of local cooling through a cloth composite electrode to terminate ventricular tachycardia. The tracings, from top to bottom, are ECG leads I and aVF, recordings from epicardial ischemic zone (epi IZ) composite electrode centered over an ice termination site and epicardial normal zone (epi NL) composite electrode in normal lateral epicardium, and time (major ticks 50 msec, minor ticks 10 msec). During cooling with an ice probe with a 1 cm diameter tip through the cloth epi IZ composite electrode, the cycle length of ventricular tachycardia increased from 215 to 240 msec, and then terminated with return to normal sinus rhythm. Note the change in the pattern of bridging diastolic electrical activity in the epi IZ composite electrogram (arrow) just before termination of ventricular tachycardia by local cooling.

FIGURE 5. Example of local cooling through a cloth composite electrode that terminated ventricular tachycardia. The ECG and electrogram orientation and labeling are the same as in figure 4. Note that local cooling through the epi IZ composite electrode changed the surface ECG QRS morphology, and increased the cycle length of this ventricular tachycardia from 215 to 250 msec before terminating it. Note also the change in the pattern of middle to late diastolic electrical activity in the epi IZ composite electrogram just before ventricular tachycardia termination. A second morphologically distinct ventricular tachycardia having a faster rate was also induced in the same dog, and is shown in figure 6.

The correlation of bridging or late diastolic epicardial electrical activity with the ability to terminate ventricular tachycardia by local epicardial cooling is shown in figure 8 and was statistically significant (p < .005 by chi-square test).

Results of depth of cooling experiments. The results of depth of cooling experiments are graphically summa-
FIGURE 6. Example of local pressure terminating ventricular tachycardia. The ECG and electrogram orientation and labeling are the same as in figure 4. Local pressure applied through the epi IZ composite electrode terminated ventricular tachycardia. Note that there was no change in the cycle length or pattern of bridging diastolic electrical activity before pressure termination of this ventricular tachycardia. This same ventricular tachycardia could also be terminated by local cooling. The site at which local cooling and pressure terminated this ventricular tachycardia was the same, but was located 3 cm from the site at which cooling terminated the ventricular tachycardia shown in figure 5, which was induced in the same dog.

FIGURE 7. Roving composite electrode (left) and local close bipolar electrograms (right) recorded from the anteroseptal, anterobasilar, anterolateral, and anteroapical infarction and its borders. The tracings, from top to bottom, are time (50 msec tics), surface ECG leads 1 and lead avF, right ventricular reference (RV) close bipolar electrograms obtained from the anteroseptal, basilar, lateral, and apical infarct and its borders (left), and local close bipolar electrograms obtained from the center of the same zones (right). The figures were reconstructed by aligning the roving composite and bipolar electrograms to the onset of the QRS in the RV reference electrogram (solid vertical lines). Note that bridging diastolic electrical activity was recorded from the anterobasal composite electrode on the left, and a discrete middiastolic electrogram was recorded from the center of the same zone on the right. The four composite electrode locations completely covered the epicardial surface of the infarction and its borders. Local epicardial cooling terminated this ventricular tachycardia in the anterobasal area in the location of recording the middiastolic local electrogram shown on the right. There was slight variation in the ventricular tachycardia cycle length.
normal zone epicardium at a depth of 0 mm was cooled by $-18 \pm 3.1\,^\circ C$ (mean $\pm$ SEM) compared with $-17.5 \pm 2.1\,^\circ C$ in infarcted muscle; in the subepicardium at a depth of 2 to 3 mm normal muscle was cooled by $-4.2 \pm 2.3\,^\circ C$ vs $-3.3 \pm 1.9\,^\circ C$ in infarcted muscle; in the midmyocardium at a depth of 5 to 7 mm normal muscle was cooled $-1.3 \pm 1.3\,^\circ C$ vs $-1.1 \pm 0.5\,^\circ C$ in infarcted muscle; and in the subendocardium at depths of 10 to 11 mm normal muscle cooled $-0.2 \pm 0.4\,^\circ C$ vs $-0.6 \pm 0.6\,^\circ C$ in infarcted muscle. There was no statistically significant difference in the degree of cooling of normal vs infarcted myocardium at any depth.

Results of microelectrode studies. The results of the microelectrode studies are presented in table 1. The action potential amplitudes of cells in the border zones and ice termination sites were significantly reduced compared with in the normal zone. Compared with in the normal zones, the maximum diastolic potentials of cells in the border zones and at ice termination sites were significantly reduced. There was no difference between action potential amplitudes and maximum diastolic potentials in the border zones vs the ice termination sites. There was also no statistically significant difference in the action potential durations at 100% repolarization in the normal zones, border zones, or ice termination sites. Compared with in the normal zone,
TABLE 1
Transmembrane potential and conduction times in epicardial, normal border, and ice termination zones

<table>
<thead>
<tr>
<th></th>
<th>Normal zone</th>
<th>Border zone</th>
<th>Ice termination zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action potential</td>
<td>88.3 ± 1.0</td>
<td>73.6 ± 1.5a</td>
<td>76.1 ± 1.7a</td>
</tr>
<tr>
<td>amplitude (mV)</td>
<td>(20)</td>
<td>(64)</td>
<td>(64)</td>
</tr>
<tr>
<td>Maximum diastole</td>
<td>72.5 ± 3.5</td>
<td>67.3 ± 1.3b</td>
<td>69.7 ± 1.6b</td>
</tr>
<tr>
<td>potential (mV)</td>
<td>(22)</td>
<td>(59)</td>
<td>(61)</td>
</tr>
<tr>
<td>Action potential</td>
<td>150.4 ± 7.4</td>
<td>161.4 ± 7.0c</td>
<td>157.5 ± 4.8c</td>
</tr>
<tr>
<td>duration at 100%</td>
<td>(23)</td>
<td>(47)</td>
<td>(46)</td>
</tr>
<tr>
<td>repolarization (msec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conduction time</td>
<td>11.9 ± 1.3</td>
<td>48.0 ± 4.5b</td>
<td>61.3 ± 4.0b</td>
</tr>
<tr>
<td>(msec)</td>
<td>(20)</td>
<td>(67)</td>
<td>(64)</td>
</tr>
</tbody>
</table>

All values are mean ± SEM. Numbers in parentheses indicate the number of impalements or measurements. The statistical analysis used was a one-way analysis of variance, with subgroup analysis by the Newman-Kuels test.

*p < .05 vs normal zone; *p < .01 vs normal zone; CNS.

conduction times were significantly prolonged in the border zone and ice termination site. There was no significant difference in conduction time in the border zones when compared with ice termination sites. When the temperature of the Tyrode perfusate was lowered from 37°C to 27°C, conduction slowed in the border zones and ice termination sites to the point of complete block in all 10 preparations studied. An example of cooling-induced slowing of conduction to the point of complete block is shown in figure 10. As illustrated, there was a 10 mV increase in amplitude in the action potential recorded from ME 2 during cooling from 37°C to 32°C over 20 min. Increase in action potential amplitude with cooling over time was not a consistent finding. There was no spontaneous automaticity or phase 4 depolarization in any of the 10 preparations studied and no sustained arrhythmias were induced by the 15-beat pacing protocol used.

Discussion

Gallagher et al.9, 10 have used local cooling to 0°C to locate the His bundle and atrioventricular accessory pathways. Scherf11 first used local cooling to temporarily suppress aconitine-induced automatic ventricular tachycardia. He applied a few crystals of aconitine to the epicardial right ventricular surface, which caused ventricular tachycardia within 1 to 2 min. Cooling of the site of application stopped ventricular tachycardia abruptly, but the arrhythmia reappeared within seconds to minutes after termination of cooling, suggesting an automatic origin. Gallagher et al.12 reported a single case of local cooling to locate the site of origin of an automatic ventricular tachycardia in a patient with scleroderma. Local epicardial cooling to 0°C terminated ventricular tachycardia with resumption of the tachycardia on rewarming. Camm et al.13, 14 reported two patients in whom local cooling terminated paroxysmal ventricular tachycardia. Although not conclusive, electrogram mapping studies of one of Camm’s patients suggested ventricular tachycardia was of a focal rather than reentrant origin.15 Mason et al.16 reported a single patient with ventricular tachycardia in whom intraoperative mapping suggested a macroreentrant etiologic profile. Cooling of tissue thought to

FIGURE 10. Example of cooling-induced slowing of conduction time to the point of complete block. A, Conduction time in the border area (pacemaker to ME 2) and in the ice termination site (ME 2 to ME 3) measured 160 and 60 msec at 37°C. B, The temperature of the Tyrode perfusate was lowered to 32°C, with increase in conduction times in the border area and ice termination site to 190 and 70 msec. C, Further cooling to 30°C caused complete block in the border area. Pacing continued to cause visible contraction of the normal zone, ruling out cooling-induced inexcitability at the site of the pacing electrode. In the same preparation, conduction time at 37°C in the normal zone was 10 msec.
contain the slow-conducting limb of the reentry loop reproducibly terminated the arrhythmia. However, this ventricular tachycardia also promptly returned on rewarming, which would suggest a focal rather than reentrant etiologic profile.

In our study local cooling was used to locate the site of maintenance and termination of reentrant ventricular tachycardia in dogs with myocardial infarction. Although a reentrant cause for the ventricular tachycardia produced in this dog infarct preparation is not totally proven, the evidence is substantial. The ventricular tachycardia could be initiated and terminated by programmed pacing, and local bridging or middle-to-late diastolic electrical activity could be recorded at the ice termination sites during ventricular tachycardia with electrogrogram mapping. These characteristics have previously been used as indirect evidence of re-entry. In addition, in vitro microelectrode evidence of slow conduction at ice termination sites progressing to complete block with cooling suggests that local cooling terminated ventricular tachycardia by slowing or blocking conduction in a reentry loop. The absence of spontaneous automaticity, phase 4 depolarization, or delayed afterdepolarizations at ice termination sites in vitro strongly militate against spontaneous or triggered abnormal automaticity or delayed afterdepolarizations as the mechanism of ventricular tachycardia in this model. Two modes of cooling-induced termination of ventricular tachycardia were seen in vivo. In the first, local cooling slowed the cycle length of ventricular tachycardia and changed the interectopic pattern of diastolic electrical activity just before termination of the arrhythmia without a change in surface ECG QRS complex (figure 4). This observation suggests that cooling slowed conduction in the same reentry pathway used to maintain the sustained arrhythmia. In the second mode, local cooling slowed the cycle length of ventricular tachycardia with change in both the interectopic pattern of diastolic electrical activity and surface ECG QRS complex just before termination (figure 5). This observation suggests that cooling slowed or modified conduction in the original reentry pathway used to maintain the arrhythmia, and caused a change to a different, less stable, reentry pathway or underlying automatic rhythm just before termination. In all cases in vivo, after local cooling terminated ventricular tachycardia it did not spontaneously reoccur on rewarming, and this would be expected if it was of automatic origin. Repeat programmed stimulation was required to reinitiate all ventricular tachycardias terminated by local cooling.

We have induced ventricular tachycardia by programmed right ventricular stimulation in steroid-pre-treated dogs 4 to 8 days after onset of infarction with facilitation of induction by lidocaine. The mechanism of drug facilitation of ventricular tachycardia induction is unknown. In order to rule out the possibility that falling lidocaine levels rather than local cooling stopped the ventricular tachycardia, we used the strict criterion of requiring three terminations of each morphologically distinct ventricular tachycardia at a specific site before labeling it an ice termination site. We have also shown that local epicardial cooling significantly shortened the natural length of programmed stimulation–induced lidocaine-facilitated sustained ventricular tachycardia.

Ice mapping study results correlated well with those of electrogrogram mapping studies in locating the site of maintenance of ventricular tachycardia. Bridging or late diastolic activity was recorded by the composite and local bipolar electrodes from 27 of 31 ice termination sites. Conversely, of 15 ventricular tachycardias without evidence of any epicardial diastole electrical activity during the arrhythmia, local cooling terminated the arrhythmia in only three. In these three instances, either the composite and bipolar electrodes failed to record diastolic electrical activity, or the reentry loop did not involve the epicardium. In two of these three instances, the ice termination area was located over a thin (2 to 3 mm thick) apical myocardium. The depth-of-cooling experiments indicated that 3° to 5° C of cooling could be achieved at the subepicardial depths of 2 to 3 mm, and that 1° to 2° C of cooling could be achieved at the midmyocardial depth of 5 to 7 mm. The magnitude of temperature lowering needed to terminate ventricular tachycardia is unknown. Therefore, in these three instances cooling may have penetrated thin myocardium to interrupt a midmyocardial or subendocardial reentry loop.

We have referred to the site of maintenance rather than site of origin of ventricular tachycardia. If ventricular tachycardia is maintained by slow conduction over a reentrant loop of finite length, then local cooling of any portion of the loop would be expected to terminate the arrhythmia. Thus, the site of origin of a reentry loop, defined as the earliest point of activation before the QRS complex in ventricular tachycardia, would not necessarily be the only site at which local cooling could terminate the arrhythmia. In our experiments, local cooling terminated the ventricular tachycardia in areas of epicardium, showing diastolic electrical activity by composite and local close bipolar electrogram mapping. These data suggest that local cooling modified conduction in diastolic portions of
the reentry loop responsible for the arrhythmias. The results of this study suggest that ice mapping can be used as a clinical or research tool to locate myocardial sites responsible for maintaining reentry. Ice mapping can be accomplished relatively rapidly, it does not require intraoperative electronic recording devices or electronic expertise, and it can provide physiologic verification of localization of a reentry loop by termination of the ventricular tachycardia before the excision or cryoablation of the suspected muscle area.

In conclusion, we have used a technique of ice mapping to localize the site of maintenance of sustained ventricular tachycardia in dogs 1 week after onset of myocardial infarction. The data presented suggest that the mechanism responsible for ventricular tachycardia in our 4 to 8 day canine infarct preparation is reentry, and that local cooling terminated ventricular tachycardia by slowing or blocking conduction in the reentry loop.

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