High-Density Mapping of Ventricular Scar
A Comparison of Ventricular Tachycardia (VT) Supporting Channels With Channels That Do Not Support VT

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Background—Surviving myocytes within scar may form channels that support ventricular tachycardia (VT) circuits. There are little data on the properties of channels that comprise VT circuits and those that are non-VT supporting channels.

Methods and Results—In 22 patients with ischemic cardiomyopathy and VT, high-density mapping was performed with the PentaRay catheter and Ensite NavX system during sinus rhythm. A channel was defined as a series of matching pace-maps with a stimulus (S) to QRS time of ≥40 ms. Sites were determined to be part of a VT channel if there were matching pace-maps to the VT morphology. This was confirmed with entrainment mapping when possible. Of the 238 channels identified, 57 channels corresponded to an inducible VT. Channels that were part of a VT circuit were more commonly located within dense scar than non-VT channels (97% versus 82%; P=0.036). VT supporting channels were of greater length (mean±SEM, 53±5 versus 33±4 mm), had higher longest S-QRS (130±12 versus 82±12 ms), longer conduction time (103±14 versus 43±13 ms), and slower conduction velocity (0.87±0.23 versus 1.39±0.21 m/s) than non-VT channels (P<0.001). Of all the fractionated, late, and very late potentials located in scar, only 21%, 26%, and 29%, respectively, were recorded within VT channels.

Conclusions—High-density mapping shows substantial differences among channels in ventricular scar. Channels supporting VT are more commonly located in dense scar, longer than non-VT channels, and have slower conduction velocity. Only a minority of scar-related potentials participate in the VT supporting channels. (Circ Arrhythm Electrophysiol. 2014;7:90-98.)

Key Words: catheter ablation ■ ischemic cardiomyopathy ■ substrate ablation ■ tachycardia, ventricular

Scar-related re-entry is the most common mechanism of ventricular tachycardia (VT) in patients with ischemic cardiomyopathy (ICM).1,2 The complex electroanatomic structure of scar,3,4 with a meandering network of surviving myocyte channels interspersed in fibrous tissue, results in discontinuous and anisotropic slow conduction that lead to the development of re-entrant VT.5,6 In clinical studies, these channels can be identified by several methods. Entrainment mapping has long been regarded as the gold standard but has limitations, in particular the need for hemodynamic stability. Pacing during sinus rhythm within dense scar can also identify channels.9,10 Areas of paced latencies ≥40 ms in scar are observed to collocate with isthmus sites, identified by entrainment mapping in patients with hemodynamically stable VT in ICM.9 Similarly, bands of relatively preserved voltages in the scar have been shown to pair with slow conducting zones within the scar.11-13 Many of these channels exhibit isolated potentials and fractionated electrograms that are often targeted during substrate-based ablation.14-16

Recent substrate ablation strategies use high-density mapping with an objective to map and eliminate all scar-related abnormal electrograms.16,17 However, because only a finite number of sustained VT ensue in the setting of healed myocardial infarction, it is likely that only a subgroup of these channels will have satisfactory electrophysiological properties to perpetuate re-entrant VT, whereas the vast majority are potential onlookers.18-20 In this study, we performed high-density characterization of the electrophysiological substrate in patients with ICM and recurrent VT. We hypothesized that differences in the anatomy and physiology between channels will explain their differential likelihood to perpetuate re-entrant VT. In addition, we examined the association between these channels and the scar-related abnormal electrograms that may give an insight into substrate ablation techniques.

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Original Article

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Methods
This study was approved by the Human Research Ethics Committee of the Royal Adelaide Hospital and the University of Adelaide.

Patient Population
Twenty-two consecutive patients with ICM with recurrent VT or VT storm (≥3 episodes or implantable cardioverter defibrillator therapies for VT in 24 hours) undergoing a clinically indicated catheter ablation procedure were studied. Patients with a previous VT ablation, acute coronary event within the preceding 1 month, intracardiac thrombus, mechanical prosthetic valve, and severe aortoiliac peripheral vascular disease were excluded.

Electrophysiological Study
The procedure was done in the postabsorptive state under conscious sedation. Briefly, a quadrupolar catheter and decapolar catheter were positioned at the right ventricular apex and coronary sinus, respectively. Programmed ventricular stimulation was performed from the right ventricular apex at 2 drive cycle lengths (600 and 400 ms) with ≤3 extrastimuli. All sustained monomorphic VTs induced at baseline, during the course of the study, and after ablation were considered clinical VT.7 A 20-pole catheter (PentaRay; 2-6-2 mm interelectrode spacing, 1 mm electrodes; Biosense-Webster Inc, Diamond Bar, CA) was introduced either retrogradely using standard sheaths or transepically using the Agilis NxT steerable introducer (St Jude Medical Inc, St Paul, MN) into the left ventricle (LV) for mapping. Activated clotting time was maintained, with intravenous unfractionated heparin, between 250 and 300 seconds throughout the course of the study. After obtaining a LV geometry on the electroanatomic mapping system (EnsiteNavX; St Jude Inc), an endocardial contact map was acquired in sinus rhythm. At each location, before signal acquisition, stability and adequate splining of the PentaRay splines over the endocardium was confirmed fluoroscopically, and ventricular ectopic beats were vigilantly excluded. Mapping was targeted to regions of low voltage (<1.5 mV), and sufficient sampling was performed elsewhere to have fill threshold of 15 mm. All points projecting >10 mm from the geometry were considered of inadequate contact and were excluded. Regular definitions were used to describe preserved voltage (≥20 ms after the end of surface QRS). Fractionated (multiple intrinsic deflections, amplitude ≤0.005 mV/ms), ≥3 sharp intrinsic deflections from baseline, amplitude ≥2 mV, duration <70 ms, and amplitude: duration >0.046 mV/ms), ≥3 intrinsically deflections, amplitude ≤0.5 mV, duration ≥133 ms, and amplitude: duration ≤0.005 mV/ms), ≥3 sharp intrinsic deflections from baseline, amplitude ≥2 mV, duration <70 ms, and amplitude: duration >0.046 mV/ms), ≥3 sharp intrinsic deflections from baseline, amplitude ≥2 mV, duration <70 ms, and amplitude: duration >0.046 mV/ms), ≥3 sharp intrinsic deflections from baseline, amplitude ≥2 mV, duration <70 ms, and amplitude: duration >0.046 mV/ms). Electrograms were classified according to the standard criteria7 as follows:

1. normal (≤3 sharp intrinsic deflections from baseline, amplitude ≥2 mV, duration <70 ms, and amplitude: duration >0.046 mV/ms),
2. fractionated (multiple intrinsic deflections, amplitude ≤0.5 mV, duration ≥133 ms, and amplitude: duration ≤0.005 mV/ms),
3. late (isolated component ≥200 ms after the end of surface QRS),
4. very late potentials (isolated component >100 ms after the end of surface QRS).

Radiofrequency Ablation
Catheter ablation then proceeded with 3.5 mm tip irrigated ablation (CoolFlex, St Jude or Thermocool, Biosense-Webster) targeting abnormal scar-related electrograms and sites with long S-QRS intervals. Programmed ventricular stimulation was repeated after catheter ablation to evaluate procedural success. Complete success was defined as no inducible VT after ablation, abolition of ≥1 clinical VTs with other VTs remaining inducible was considered a partial success, and the inability to eliminate the clinical VT was considered as a failure.

Postprocessing of Maps
The surface areas of low voltage and dense scar were measured using the integrated software. Offline analysis of the digitally stored electrograms and pace maps was performed on the Bard EP system with the use of on-screen calipers at a sweep speed of 200 mm/s. Electrogram timing, duration, and peak-to-peak voltage were measured manually, and the locations of fractionated, late, and very late potentials were registered on the electroanatomic surface. Pace-maps were physically searched and matched for ≥11/12 lead matches in the surface ECG QRS morphology. If the morphology matched a spontaneous or inducible VT, it was considered as a VT channel, otherwise it was classified as non-VT channel. The S-QRS interval was measured manually to the onset of QRS in the ECG lead with the shortest S-QRS.9 A channel was fashioned from an orthodromically activated sequence of identical pace maps, including a minimum of 2 pace maps, with ≥1 pace map having a S-QRS ≥40 ms.7 So as not to overestimate the channel length, the shortest endocardial distance, joining ≥60% of the pertinent pace maps, was used (Figure 1). This distance was determined using the incorporated software and was recorded as channel length. The remainder of the pace maps, if any extending beyond 1 cm of the main length, was considered as joint annexes to the channel. In stable VT, a channel was constructed connecting entrainment locations reasoned from isthmus sites in an orthodromic order of S-QRS latencies.7 Conduction time and conduction velocity in the channel were ascertained as the difference between the longest and shortest S-QRS interval and the ratio of channel length to conduction time, respectively.

A pace-map location with multiple QRS morphologies was considered as a shared segment if remote pace-map locations with QRS morphologies corresponding to the index pace-map existed. Furthermore, if 2 channels were perceived to cross each other on the anatomic surface, they were considered having a shared endocardial segment. As activation can exit in either direction of a channel with

Figure 1. Schematic for definitions used in the study. Green circles represent the full set of pace maps performed in dense scar (gray) and borderzone. Pace maps with matching ≥11/12 leads) surface ECG QRS morphology (solid white circles, 1–10) are connected in an orthodromic order of stimulus-QRS (S-QRS) interval latency (longest S-QRS [1] to shortest S-QRS [1] linking ≥60%) identical pace maps in a minimal endocardial pathway (white arrow). This was considered as the length of the channel. The remaining pace maps (6 and 7) extending >10 mm across channel were considered as joined annexes (red arrow) to the channel. Pace-map location with multiple exiting QRS morphology was considered as shared (blue circle, 5) if remote pace maps matching the index QRS morphologies were present.
different QRS morphology, this may erroneously classify segments of VT channels as non-VT channels. To reduce such possibility, the electroanatomic properties of isolated non-VT channels that did not have any shared pace maps or shared anatomic segments with VT channels (referred to as unshared non-VT channels) were separately compared with VT channels.

Small confluent areas (≥2 sampled points) of relatively preserved voltage (>0.5 mV) surrounded by dense scar were referred to as islets, and their relationship with channels was determined.26 Fractionated and late potentials were considered related to a channel location if they were sited within 1 cm of the channel and their joint annexes.

Follow-Up
All patients had or received implantable cardioverter defibrillators and were monitored clinically at 3 monthly follow-ups with device interrogation. Recurrence was defined as the occurrence of sustained VT or appropriate implantable cardioverter defibrillator therapies.

Statistical Analysis
Baseline parameters are presented as mean±SD, proportion, and median with interquartile range (IQR) for continuous, categorical, and count variables, respectively. Comparisons were done using independent sample Student t test, χ² test (or Fisher exact test where applicable), or Mann–Whitney U test as appropriate. To account for intrapatient clustering of data and interpatient differences, linear and nonlinear mixed-effects models, clustered by patient identity (random effect), were used to examine the effect of channel type (fixed effect) on each of the outcomes. Because several S-QRS intervals were recorded for each channel, to account for clustering within a channel, channel count within patient was also included as a random effect in the model comparing S-QRS interval values between channel types. Linear, logistic, and negative binomial mixed-effects models were used to explore the continuous, dichotomous, and count outcomes, respectively. The results estimated from models are presented as mean±SEM for each of the outcomes. The measure of agreement between VT channel locations and their relationship with channels was determined.26 Fractionated and late potentials were considered related to a channel location if they were sited within 1 cm of the channel and their joint annexes.

Results
Baseline Clinical Characteristics
The baseline characteristics of the 22 patients are presented in Table 1. All patients had undergone a recent noninvasive evaluation or coronary angiography to exclude active ischemia.

Inducible VT
Programmed ventricular stimulation was performed a median of 3 times (IQR, 2–5) during the study. All patients had ≥1 inducible or spontaneous sustained monomorphic VT at baseline. Overall 73 different VTs were inducible, a median of 3 (IQR, 2–5) VTs per patient, with a mean cycle length of 396±110 ms.

LV Endocardial Voltage Mapping
A mean number of 760±205 sampling points were taken per patient with 431±137 points within dense scar. Of the total LV area (324±69 cm²), 60±15% (204±73 cm²) had low voltage, and 37±11% (128±56 cm²) was formed by dense scar. Islets of relatively preserved voltages (median, 3; IQR, 1–4 per patient; mean voltage, 1.2±1 mV) were identified within dense scar in 20 of the 22 patients.

Table 1. Baseline Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>N</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>22</td>
<td>67±10</td>
</tr>
<tr>
<td>Men, n (%)</td>
<td>21</td>
<td>95</td>
</tr>
<tr>
<td>Ejection fraction, %</td>
<td>32±8</td>
<td></td>
</tr>
<tr>
<td>Time to first infarction, y</td>
<td>14±10</td>
<td></td>
</tr>
<tr>
<td>Coronary bypass surgery, n (%)</td>
<td>11</td>
<td>50</td>
</tr>
<tr>
<td>Rhythm, n (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinus rhythm</td>
<td>18</td>
<td>(82)</td>
</tr>
<tr>
<td>Atrial fibrillation</td>
<td>1</td>
<td>(4)</td>
</tr>
<tr>
<td>Ventricular paced rhythm</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>QRS duration, ms</td>
<td>143±37</td>
<td></td>
</tr>
<tr>
<td>VT cycle length, ms</td>
<td>384±116</td>
<td></td>
</tr>
<tr>
<td>VT storm, n (%)</td>
<td>7</td>
<td>32</td>
</tr>
<tr>
<td>Previous ICD, n (%)</td>
<td>19</td>
<td>86</td>
</tr>
<tr>
<td>β-Blocker, n (%)</td>
<td>20</td>
<td>91</td>
</tr>
<tr>
<td>Amiodarone, n (%)</td>
<td>13</td>
<td>(59)</td>
</tr>
<tr>
<td>Other antiarrhythmic drugs (sotalol, mexiletine), n (%)</td>
<td>8</td>
<td>36</td>
</tr>
</tbody>
</table>

Data presented as mean±SD. ICD indicates implantable cardioverter defibrillator; and VT, ventricular tachycardia.

Mapping of Channels

Pace Mapping
Pace mapping was performed in low-voltage zones at 2507 sites and median 91 (IQR, 60–162) per patient. Capture was absent at 670 sites (27%) and median 23 (IQR, 13–50) per patient. Of the captured sites, 1076 sites (median, 38; IQR, 19–61 per patient) had S-QRS interval ≥40 ms that led to the construction of channels. Figure 2 illustrates the pace-map series for an inducible VT. The distribution of pace maps among various channel types is given in Table 2 and Figure 3. Overall, 428 pace maps corresponded to 57 inducible VTs that formed the VT channel group, whereas 838 pace maps belonged to the non-VT channel group. Matching pace maps to 16 inducible VTs could not be found. Despite relatively uniform pace mapping density in the scar, the mean pace-map count was higher in the VT channels (mean, 7 [95% CI, 5.4–10.2]) when compared with the non-VT channel group (mean, 4 [95% CI, 3.1–5.0]; P=0.0001). Pace maps with S-QRS interval ≥40 ms (mean, 6 [95% CI, 4.4–8.4]) and ≥80 ms (mean, 1 [95% CI, 0.7–2.7]) were more frequent in VT channels when compared with that in non-VT channels (mean, 4 [95% CI, 2.7–4.5] and mean, 0.5 [95% CI, 0.3–1.0] respectively; P<0.001). These differences achieved greater significance when comparison was restricted to the unshared non-VT channels. Beat-to-beat variations in the S-QRS intervals were occasionally observed as varying degrees of exit block at paced sites with long latencies in the VT channel group.

Entrainment Mapping
Entrainment mapping was feasible in 11 patients who had ≥1 potentially mappable VT. Overall, at the entrainment locations, diastolic potentials covering 52±22% of tachycardia cycle length could be identified within the PentaRay mapping catheter area. The participation of these diastolic potentials in
the tachycardia circuit was demonstrated, and isthmus locations could be confirmed in 6 VTs (Figure 4).

**VT Channels**

The comparison between electroanatomic properties of VT channels, non-VT channels, and unshared non-VT channels are presented in Table 3. Fifty-seven VT channels (median, 2; IQR, 1.8–4 per patient) were identified. Fifty-four VTs could be mapped in the LV, whereas 3 had matching pace maps in the right ventricle. The majority (97%) of these channels are resided in the dense scar, with 48% of channels having segments extending into the borderzone. Islets of relatively preserved voltages were identified in the close proximity to 40% of VT channels. The majority of the dense scar area had voltages between 0.1 and 0.5 mV and so altering the voltage to this range did not identify VT channels. Twenty VT channels (35%) had shared pace-map locations (4 channels) or shared anatomic segments (16 channels) with at least one another VT channel. The odds of finding a longest S-QRS interval of >80 ms were 5.9× greater in a VT channel relative to an unshared non-VT channel (95% CI, 2.6–13.6; \(P<0.0001\)). The joint annexes to the VT channels, identified in 24 VT channel regions, extended a mean of 18±7 mm beyond the main length of the channel.

**Non-VT Channels**

All non-VT channels were mapped in the LV. Overall, 183 non-VT channels (median, 6; IQR, 5–11 per patient) were identified, with an average of 4.6 (95% CI, 2–7) non-VT channels in a patient per VT channel. This included 33 non-VT channels that shared pace maps (9 channels) or had shared anatomic segments with a VT channel (24 channels). The remaining 150 non-VT channels (median, 5.5; IQR, 5–9 per patient) belonged to the unshared non-VT channel group. The mapped VT and non-VT channels in a case example are illustrated in Figure 5.

Unlike VT channels, unshared non-VT channels had a wider distribution with 18% found in the borderzone voltage regions (\(P=0.02\)). Most of these channels (112/150; 75%) were located beyond 1 cm of the VT channel regions. Islets of preserved voltages were identified in close proximity to a smaller proportion of unshared non-VT channel (95% CI, 2.6–13.6; \(P<0.0001\)). The joint annexes to the unshared non-VT channels, identified in 24 channel regions, extended a mean of 18±7 mm beyond the main length of the channel.

### Table 2. Distribution of Pace-Maps Among VT and Non-VT Channels

<table>
<thead>
<tr>
<th>Property</th>
<th>VT Channels</th>
<th>Non-VT Channels</th>
<th>(P) Value*</th>
<th>Unshared Non-VT Channels</th>
<th>(P) Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pace-map count, n</td>
<td>428</td>
<td>838</td>
<td>...</td>
<td>613</td>
<td>...</td>
</tr>
<tr>
<td>Number per channel</td>
<td>7 (5.4, 10.2)</td>
<td>4 (3.1, 5.0)</td>
<td>0.0001</td>
<td>4 (2.8, 4.5)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Pace maps with S-QRS≥40 ms (%)</td>
<td>360 (84)</td>
<td>774 (92)</td>
<td>...</td>
<td>562 (92)</td>
<td>...</td>
</tr>
<tr>
<td>Number per channel</td>
<td>6 (4.4, 8.4)</td>
<td>4 (2.7, 4.5)</td>
<td>0.0008</td>
<td>3 (2.4, 4.0)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Pace maps with S-QRS≥80 ms (%)</td>
<td>123 (29)</td>
<td>191 (23)</td>
<td>...</td>
<td>138 (23)</td>
<td>...</td>
</tr>
<tr>
<td>Number per channel</td>
<td>1 (0.7, 2.7)</td>
<td>0.5 (0.3, 1.0)</td>
<td>0.0004</td>
<td>0.4 (0.2, 0.8)</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Data presented as \(x (y, z)\) format represent mean count (95% confidence interval). S-QRS indicates stimulus-QRS interval; and VT, ventricular tachycardia.

*vs VT channels.
Abnormal electrograms were frequently identified in low-voltage zones in these patients (Table 4). On average, of all sampled data points, fractionated, late, and very late potentials were present at 16±11%, 1.5±0.9%, and 0.6±0.8% of sites, respectively. However, of all the fractionated (median, 105; IQR, 54–220), late (median, 10; IQR, 6–13), and very late (median, 2; IQR, 1–6) potentials, only 21%, 26%, and 29%, respectively, were recorded in the VT channels. These electrograms had poor sensitivity but high specificity for locating a VT channel: fractionated potential 44% and 86%, late potential 4% and 99%, and very late potential 2% and 99%, respectively. There was relatively poor agreement between abnormal electrogram site and a channel location (fractionated potential, κ=0.2; late potential, κ=0.05; and very late potential, κ=0.03). Importantly, however, when compared with elsewhere within the scar, VT channels demonstrated longer fractionated potentials (105±2 versus 95±2 ms; P<0.0001) and poorly coupled very late potentials (311±31 versus 226±23 ms; P=0.030), but there was no difference in the coupling intervals of late potentials (P=0.82).

Ablation Outcomes

Complete procedural success was achieved in 14 (64%) patients and partial success in 7 (32%) patients. Among those with complete success, 3 patients with 7 VTs had 4 VTs that could not be successfully mapped but were still eliminated by catheter ablation. Only 4 patients continued antiarrhythmic medications after the procedure. For long-term follow-up of 16±6 months, 3 patients died of heart failure, and 5 (23%) had recurrence of VT. Of those with VT recurrence, 2 patients had a completely successful and 3 patients a partially successful first procedure.

Inducible VT During Repeat Procedures

Four patients underwent repeat catheter ablation for a median of 2 months after the first ablation. During repeat procedures, there were 11 inducible VTs (median, 3 VTs per patient), of which 8 were completely new, 2 matched a previous VT, and 1 matched a previous shared non-VT channel morphology. None of the new VTs during repeat procedures matched a previous unshared non-VT channel morphology.

Discussion

Major Findings of the Study

This study used a high density of sampling and rigorous pace mapping with small bipoles to characterize the ventricular scar. It showed significant differences in the electroanatomic properties between VT supporting and non-VT channels in patients with ICM and monomorphic VT. When compared with non-VT channels, VT channels were

1. more commonly located within dense scar;
2. longer in length;

![Figure 4. Entrainment pacing (channel B2,3) and its termination during a ventricular tachycardia (VT). Channels from top to bottom are surface ECG (I, III, V1, V5), PentaRay mapping catheter in left ventricular scar region (A1,2–E3,4), and right ventricular apex (RVA, distal [d] and proximal [p]). Intervals are marked in milliseconds. This pacing site entrained the VT with concealed fusion with a stimulus-QRS (S-QRS) interval of <30% of the tachycardia cycle length, S-QRS matching the electrogram-QRS interval and the difference between after pacing interval and tachycardia cycle length is 0 ms. The diastolic potentials seen on the PentaRay channels during tachycardia (arrows) covered 202 ms (44%) of the tachycardia cycle length. This site represented isthmus near its exit for this VT.

<p>| Table 3. Comparison of Electroanatomic Properties of VT and Non-VT Channels |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th><strong>Property</strong></th>
<th><strong>VT Channels</strong></th>
<th><strong>Non-VT Channels</strong></th>
<th><strong>P Value</strong></th>
<th><strong>Unshared Non-VT Channels</strong></th>
<th><strong>P Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total number</strong></td>
<td>57</td>
<td>183</td>
<td>...</td>
<td>150</td>
<td>...</td>
</tr>
<tr>
<td><strong>Number per patient</strong></td>
<td>2 (1.8, 4)</td>
<td>6 (5, 11)</td>
<td>&lt;0.0001</td>
<td>5.5 (5, 9)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>Location in scar, %</strong></td>
<td>97 (84, 99)</td>
<td>85 (69, 90)</td>
<td>0.064</td>
<td>82 (62, 90)</td>
<td>0.036</td>
</tr>
<tr>
<td><strong>Longest S-QRS, ms</strong></td>
<td>130±12</td>
<td>85±12</td>
<td>&lt;0.0001</td>
<td>82±12</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>95th percentile value</strong></td>
<td>360</td>
<td>136</td>
<td>...</td>
<td>134</td>
<td>...</td>
</tr>
<tr>
<td><strong>Any S-QRS, ms</strong></td>
<td>73±4</td>
<td>63±3</td>
<td>0.020</td>
<td>63±3</td>
<td>0.018</td>
</tr>
<tr>
<td><strong>95th percentile value</strong></td>
<td>161</td>
<td>108</td>
<td>...</td>
<td>108</td>
<td>...</td>
</tr>
<tr>
<td><strong>Length, mm</strong></td>
<td>53±5</td>
<td>34±4</td>
<td>0.0004</td>
<td>33±4</td>
<td>0.0003</td>
</tr>
<tr>
<td><strong>Conduction time, ms</strong></td>
<td>103±14</td>
<td>47±13</td>
<td>&lt;0.0001</td>
<td>43±13</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>Conduction velocity, m/s</strong></td>
<td>0.87±0.23</td>
<td>1.30±0.21</td>
<td>0.022</td>
<td>1.39±0.21</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Data presented as x(y, z) format represent mean proportion (95% confidence interval), except channel number per patient which is median (interquartile range). Data presented as x±y format represent mean±SEM. S-QRS indicates stimulus-QRS interval; and VT, ventricular tachycardia.

*vs VT channels.
3. had slower conduction velocity with longer conduction times; and
4. more commonly colocated with islets of relatively preserved voltages.

In addition, abnormal electrograms were abundant in the scar but only a small proportion was located in the region of VT channels. Electrograms at these sites displayed a longer duration of fractionation and poorer coupling of very late potentials relative to elsewhere in the scar. These observations may, in part, explain the difference in propensity of only few surviving myocyte channels in the scar to support re-entrant VT.

**Previous Studies**

The broad focus of a large body of clinical research in scar-related re-entry has been on channels supporting VT with a relatively limited representation of the properties of the non-VT channels. Earlier experimental studies have shown that bundles of viable myocytes interwoven with strands of fibrous tissue form preferential conduction channels with slow conduction velocity around 0.25 m/s. These channels can be identified during sinus rhythm by endocardial voltage mapping or by mapping of scar areas with pacing. Stimulus-QRS latency ≥40 ms during pacing in sinus rhythm is a well-recognized measure of slow conduction and reflects capture in protected zones before breakthrough into larger myocardium. Such slow conducting zones, particularly with latency >80 ms, irrespective of the resulting QRS morphology are considered as good markers of locations adjacent to putative isthmuses of clinical VT. Clinical studies involving mapping during hemodynamically stable VT in patients with previous MI report average isthmus lengths of ~30 mm, with 90% of isthmuses found in the scar, whereas entrance and exits sites are found in border-zone or normal myocardium. Arenal et al identified channels by adjusting voltages within the apparently dense scar (from 0.5 to 0.1 mV) and reported an average channel length of 23±11 mm and width of 9±3 mm. These corridors of...
relatively preserved voltages in the dense scar express long-paced S-QRS latencies and have been postulated to harbor critical components of VT circuits, and their ablation suppresses inducibility of the VT.11,13

In this study, we relied largely on pace mapping within the dense scar to track preferential propagation corridors. Altering the voltage range from 0.1 to 0.5 mV did not identify VT channels because the majority of the dense scar had voltage within this range. Channels that support VT were found to have distinctive anatomic and electrophysiological properties. These include longer lengths with slower conduction providing the conditions conducive for supporting macroreentry.5,29 The differences in the estimated length (53±31 mm) of VT conducting channels in our study, when compared with previous studies, reflect the methodological differences. The longer channel lengths then reported in previous studies are likely because of the higher resolution of scar mapping with ≤10 pacing sites per channel, from a small, closely spaced bipole, enabling identification of the channel course in great detail. However, given that the channels may traverse the scar in a zigzag course,6 the channel lengths estimated from an orthodromic sequence of high-density pace maps would still best reflect only an apparent length.

In the present study, the identified non-VT channels outnumbered the VT channels and were widely distributed in the endocardial scar with three-quarters of the non-VT channels in the regions remote to the VT channels. This is in accordance with the widespread inhomogeneous scarring with varying degrees of preservation of subendocardial myocytes in patients with ICM.1,27 Interestingly, only a small proportion of the non-VT channels shared segments with the VT channels, and some of these may be exits from the other end of the VT channel.25 These results may indicate that only certain regions of the ventricular scar develop the necessary properties that are required to sustain re-entry.

### Scar-Related Electrograms and VT Channels

The abnormal electrograms observed in sinus rhythm from these surviving myocytes in the scar serve as indirect evidence for the channels with each peak in a multideflection bipolar electrogram, representing individual myocyte bundle conduction.6,14,30 There are data that suggest that such electrograms are frequently identified at sites where catheter ablation does not terminate VT.19,20 Conversely, only 50% of central, proximal, or exit sites of re-entry isthmuses have abnormal electrograms.15 The present study confirms these results that while abnormal electrograms were prevalent within ventricular scar, only a small proportion was related to VT supporting channels. In fact, the majority of abnormal electrograms were unrelated to any channel at all.

### Islets of Preserved Voltages and VT Channels

The voltage threshold of 1.5 mV is very specific, but has limited sensitivity in a low density map, and often fails to detect fine insulated bundles of surviving myocytes within the scar.31 High-density mapping permits identification of some of these surviving tissues as small confluent islets of relatively preserved voltages in an otherwise dense scar. Nakahara et al26 reported that 57% of the very late potentials were colocated with these islets and their peripheries, and these were commonly associated with putative isthmus sites. These islets may not necessarily participate in VT circuits; however, they may be markers of proximity to surviving myofibers that have role in perpetuation of VT. In the present study, such islets were nested around the regions of 40% of VT channels and are, therefore, potential targets for the elimination of VT.

### Clinical Implications

The contemporary substrate-based ablation practices have evolved from linear anchoring ablation,22 short lines,32 to spot

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**Table 4. Comparison of Scar-Related Electrograms in Channel Regions vs Rest of Scar**

<table>
<thead>
<tr>
<th>Electrogram Type</th>
<th>VT Channels</th>
<th>Non-VT Channels</th>
<th>Rest of Scar</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractionated potential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number (%)</td>
<td>607 (21)</td>
<td>761 (27)</td>
<td>1462 (52)</td>
<td>...</td>
</tr>
<tr>
<td>Number per channel</td>
<td>15 (10.1, 22.8)</td>
<td>16 (13.5, 19.3)</td>
<td>...</td>
<td>0.79</td>
</tr>
<tr>
<td>Duration, ms</td>
<td>105±2</td>
<td>101±2</td>
<td>95±2</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>Amplitude, mV</td>
<td>0.2±0.01</td>
<td>0.2±0.01</td>
<td>0.2±0.01</td>
<td>0.63</td>
</tr>
<tr>
<td>Late potential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number (%)</td>
<td>59 (26)</td>
<td>68 (30)</td>
<td>101 (44)</td>
<td>...</td>
</tr>
<tr>
<td>Number Per Channel</td>
<td>1.3 (0.8, 2.1)</td>
<td>0.9 (0.6, 1.2)</td>
<td>...</td>
<td>0.19</td>
</tr>
<tr>
<td>Coupling interval, ms</td>
<td>43±5</td>
<td>45±5</td>
<td>42±3</td>
<td>0.82</td>
</tr>
<tr>
<td>Very late potential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number (%)</td>
<td>26 (29)</td>
<td>7 (8)</td>
<td>58 (63)</td>
<td>...</td>
</tr>
<tr>
<td>Number per channel</td>
<td>0.3 (0.2, 0.8)</td>
<td>0.1 (0.04, 0.25)</td>
<td>...</td>
<td>0.008</td>
</tr>
<tr>
<td>Coupling interval, ms</td>
<td>311±31</td>
<td>250±59</td>
<td>226±23</td>
<td>0.030†</td>
</tr>
</tbody>
</table>

Data presented as x (y, z) format represent mean count (95% confidence interval). Data presented as x±y format represent mean±SEM. VT indicates ventricular tachycardia.

*P=0.004 VT channels vs non-VT channels, P<0.0001 VT channels vs rest of scar, P<0.0001 non-VT channels vs rest of scar.
†P=0.34 VT channels vs non-VT channels, P=0.0065 VT channels vs rest of scar, P=0.70 non-VT channels vs rest of scar.
ablative targeting areas of long paced-latencies25 or abnormal scar-related electrograms.17 However, finding and ablating these regions in the expanse of large heterogeneous scar can be time consuming. This and other studies16,26 have used multielectrode catheters enabling rapid collection of ventricular scar-related electrograms. There is also interest in a more targeted substrate ablation strategy and identifying regions within the scar important to the development of VT. This study is the first comprehensive report on the differential electroanatomic features of VT supporting and non-VT channels within the scar and may provide the basis for the development of a more focused substrate ablation. Because the majority of VT channels were mapped in regions often separate from the non-VT channels, identification of these regions may allow a limited ablation strategy. Additional analyses are required to identify these regions without extensive pace mapping or mapping during VT.

Study Limitations
Most of the VTs were poorly tolerated precluding entrainment mapping and thus, localization of the VT channels relied heavily on paced latencies. Nevertheless, pace mapping is widely considered the best surrogate to locate surviving myocyte channels25 and ultra–high-density pace mapping with rigorous matching criteria, as was applied in our study reduces this issue. Pace mapping was performed at cycle lengths longer than the VT because rapid pacing is likely to induce VT. Despite pace mapping at slower rates, which can reduce the likelihood of lines of functional block, pace-map locations matching one of the induced VT morphology were identified in most patients, signifying functional latencies likely had a limited influence on the QRS morphology in the majority of VTs. Epicardial mapping was not done because all these patients had an ischemic substrate and subendocardial scar, many with previous bypass surgery. It is likely that a proportion of VT and non-VT channels could have had intramural or epicardial circuits. We performed high-density pacing from small closely spaced bipoles in preference to unipolar pacing. This design can favorably reduce the influence of anodal capture and capture away from the pacing electrodes. The significantly low rate (6%) of noncaptured pace maps in the infarct zone reported with unipolar pacing,25 when compared with our study, upholds this proposition. Frequent use of antiarrhythmic drugs before ablation can suppress some VT during the procedure. VT induction was performed for a median of 3X per patient to reduce the prospect of omitting an inducible VT, but it is possible that some of the QRS morphologies included in the non-VT channel group may have been critical to VT morphologies that were unable to be induced. The effect of antiarrhythmic drugs on conduction delays during sinus rhythm was inevitable, but regional differences in the scar were still demonstrable. Ablation was targeted with aim of eliminating scar-related electrograms at sites of long paced latencies and the effect of differential ablation of non-VT channels on acute and long-term outcomes was not in the scope of this study. Larger studies with long follow-up are needed to determine if some non-VT channels mature to sustain VT.

Conclusions
High-density mapping in the ventricular scar enables characterization of VT supporting and non-VT channels. Channels supporting VT possess distinctive anatomic and electrophysiological properties that potentially predispose them to perpetuate re-entrant VT. Abnormal electrograms are abundant in postinfarction ventricular scar; however, the contribution by scar regions harboring clinical VT channels is small. These findings may provide a basis for more limited substrate ablation strategies.

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Clinical arrhythmia.
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