High-Resolution Mapping of Ventricular Scar
Comparison Between Single and Multielectrode Catheters

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**Background**—Mapping resolution is influenced by electrode size and interelectrode spacing. The aims of this study were to establish normal electrogram criteria for 1-mm multielectrode-mapping catheters (Pentaray) in the ventricle and to compare its mapping resolution within scar to standard 3.5-mm catheters (Smart-Touch Thermocool).

**Methods and Results**—Three healthy swine and 11 swine with healed myocardial infarction underwent sequential mapping of the left ventricle with both catheters. Bipolar voltage amplitude in healthy tissue was similar between 3.5- and 1-mm multielectrode catheters with a 5th percentile of 1.61 and 1.48 mV, respectively. In swine with healed infarction, the total area of low bipolar voltage amplitude (defined as <1.5 mV) was 22.5% smaller using 1-mm multielectrode catheters (21.7 versus 28.0 cm²; \( P=0.003 \)). This was more evident in the area of dense scar (bipolar amplitude <0.5 mV) with a 47% smaller very low–voltage area identified using 1-mm electrode catheters (7.1 versus 15.2 cm²; \( P=0.003 \)). In this region, 1-mm multielectrode catheters recorded higher voltage amplitude (0.72±0.81 mV versus 0.30±0.12 mV; \( P<0.001 \)). Importantly, 27% of these dense scar electrograms showed distinct triphasic multicomponent electrogram recorded with the 3.5-mm electrode catheter. In 8 mapped reentrant ventricular tachycardias, the circuits included regions of preserved myocardial tissue identified with 1-mm multielectrode catheters but not 3.5-mm electrode catheters. Pacing threshold within the area of low voltage was lower with 1-mm electrode catheters (0.9±1.3 mV versus 3.8±3.7 mV; \( P=0.001 \)).

**Conclusions**—Mapping with small closely spaced electrode catheters can improve mapping resolution within areas of low voltage. (Circ Arrhythm Electrophysiol. 2016;9:e003841. DOI: 10.1161/CIRCEP.115.003841.)

**Key Words:** electrodes  ■  heart  ■  myocardial infarction  ■  swine  ■  ventricular tachycardia

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The pathophysiology of infarct-related reentrant ventricular tachycardia (VT) includes myocardial cell death and ventricular remodeling, resulting in inhomogeneous scarring with variable degrees and configurations of surviving myocardial bundles within the areas of fibrosis. This provides the necessary electrophysiological substrate for formation of reentrant VTs that are predominantly located in the subendocardium.1,2

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Standard mapping catheters have several limitations for mapping scar-related VTs. These catheters have a 3.5-mm distal tip electrode that is separated by 1 mm from a proximal 1-mm electrode, resulting in a center-to-center interelectrode spacing of 3.25 mm. As such, each bipolar electrogram represents recording from an underlying tissue diameter ranging from 3.5 to 5.5 mm, depending on the angle of the catheter (from perpendicular to parallel to the tissue, respectively). This mapping resolution may not be adequate to identify surviving myocardial bundles (including isthmuses) within the area of low voltage because there may be cancellation effects of bipolar electrograms recorded within these areas.3 In addition, electrograms recorded using these relatively large electrode catheters often record long, fractionated, and multicomponent signals because of the underlying pattern of activation. The presence of such fractioned electrograms limits accurate annotation of local activation time during activation mapping and interpretation of entrainment mapping.

Catheters with 1-mm electrodes, 2-mm interelectrode spacing, and an overall 3-mm center-to-center interelectrode spacing record electrograms from a significantly smaller underlying tissue area, ranging from 1 to 4 mm. This design offers several advantages for mapping scar-related arrhythmias, including (1) higher mapping resolution that may identify heterogeneity within the area of low voltage during sinus rhythm mapping allowing localization of surviving myocardial bundles; (2) smaller electrodes with closer
WHAT IS KNOWN

- Electrogram amplitude and duration are influenced by electrode size and interelectrode spacing.
- Mapping resolution can be enhanced by catheters with smaller electrodes and closer interelectrode spacing.

WHAT THE STUDY ADDS

- This study established electrogram criteria for normal and abnormal ventricular tissue with 1-mm electrode catheters using a human-like swine model of chronic post-infarct scar.
- Mapping resolution within areas of low voltage and scar is enhanced with 1-mm multielectrode catheters in comparison to conventional 3.5-mm electrode catheters and can identify areas of preserved myocardial bundles (“channels”).
- Electrograms recorded with small and closely spaced electrodes allow identification of distinct diastolic activity during reentrant VT that may not be seen with standard mapping catheters.

interelectrode spacing are subjected to less signal averaging and cancellation effects, and may thus record electrograms with higher bipolar voltage amplitude and shorter electrogram duration, allowing more accurate local activation time annotation; and (3) pacing with capture at lower output because of increased electric current density (Figure 1).

The aims of this study were to (1) define normal voltage amplitude and electrogram duration in the ventricle for 1-mm multielectrode-mapping catheters (Pentaray), (2) compare its mapping resolution in scar to a standard 3.5-mm electrode tip catheter (Thermocool), and (3) evaluate its use for mapping postinfarction reentrant VTs in a swine model.

Methods

Experimental Study Design

This prospective study included a total of 14 swine, 3 healthy controls, and 11 with chronic anterior wall infarction. Our swine model has been previously described and closely approximates human-related subendocardial infarction and reentrant VT. In brief, Yorkshire swine (male, 30–35 kg) underwent selective balloon occlusion of the left anterior descending artery for duration of 180 minutes. After a survival period of 6 to 8 weeks, animals underwent mapping of the left ventricle (LV) during sinus rhythm, followed by electroanatomic mapping (EAM), including mapping of any hemodynamically tolerated monomorphic VT. The institutional animal care and use committee approved this research protocol.

Mapping Protocol

EAM was performed under general anesthesia using Carto 3 mapping system (Carto 3 system, Biosense Webster, Diamond Bar, CA). Mapping of the LV was performed during sinus rhythm. Initial mapping was performed using an open irrigation linear catheter with a 3.5-mm distal electrode separated by 1 mm from a 1-mm proximal electrode (Smart-Touch Thermocool, Biosense Webster; linear) in a point-by-point fashion. Electrograms were included only within a contact force range of 10 to 25 g to ensure adequate tissue contact. To ensure detailed and complete mapping of the entire chamber, we set a density fill threshold of ≤5 mm in regions of low bipolar voltage amplitude and ≤10 mm elsewhere as a requisite for a complete map. This allowed interpolation between points to be limited to <5 mm in scar and 10 mm elsewhere.

After completion of the EAM with the linear catheter, the LV was remapped with a 20-pole steerable mapping catheter arranged in 5 soft radiating spines covering a diameter of 3.5 cm (Pentaray, Biosense Webster; interelectrode spacing 2-6-2 mm; multielectrode mapping). The density fill threshold remained constant at ≤5 mm in regions of low bipolar voltage amplitude and ≤10 mm elsewhere as a requisite for a complete map. Although, the multielectrode-mapping catheter does not have contact force sensing technology, we used an internal point filter software available on the mapping system to limit data acquisition to within 5 mm from the original shell made with contact force technology. This algorithm, although not an equivalent to tissue contact, can potentially reduce mapping of cavitary structures. To calculate the low-voltage surface area, we used the measurement tool included in the mapping system software.

Electrogram Analysis

To define the lower normal voltage cutoffs in the healthy ventricle, we analyzed data from 3 healthy control swine and determined the 5th percentile of the bipolar voltage amplitude with both linear and multielectrode-mapping catheters. Bipolar signal duration was analyzed offline with electronic calipers using uniform lead gain and paper speed of 200 mm/s using Lab System Pro EP recording system (Bard, Boston Scientific, Lowell, MA). The local ventricular signal duration was measured from the earliest initial deflection from the isoelectric line to the time the last signal component returned to the isoelectric line. To compare differences in electrograms characteristics between the catheters, we analyzed signals for the presence of fractionation (defined as signals with ≥5 intrinsic deflections) and split potentials (defined as those displaying an additional signal separated from the local ventricular electrogram by ≥20 ms).

We compared the bipolar voltage amplitude and duration between the linear and multielectrode catheters in regions of low-voltage scar. To compare data points in similar location, we exported the spatial coordinate of the recording location data of each map into an in-house software written in Matlab (The MathWorks, Natick, MA) and paired data points between the linear and multielectrode catheters maps that were within ≤2 mm from each other (Figure I in the Data Supplement). Bipolar electrograms were filtered between 30 and 500 Hz, and unipolar electrograms were filtered 1 and 500 Hz.

Cardiac Magnetic Resonance Imaging

In-vivo and ex-vivo cardiac magnetic resonance (CMR) imaging was performed using a 1.5T MRI scanner (Phillips Achieva, Best, NL) with a 32-element cardiac phased array receiver coil. Cardiac anatomic study was assessed using a cardiac cine examination in short axis with steady-state free-precession imaging sequence. Three-dimensional late gadolinium enhancement images with isotropic spatial resolution of 1 mm³ were acquired 15 to 25 minutes after infusion of a bolus (2 mL/60 kg gadobenate dimeglumine (MultiHance; Bracco, Rome, Italy). Image analysis was performed using an in-house CMR analysis platform (MediACare). Endocardial and epicardial contours were manually delineated in all slices, and LV myocardial volume and LV cavity volume were directly measured.

Electrophysiology Study

After completion of the EAM, electric stimulation was performed from the right ventricle apex using a current strength twice the capture threshold and pulse width of 2.0 ms. Programmed ventricular stimulation at paced cycle lengths of 600 and 400 ms with 1 to 4 extrastimuli down to ventricular effective refractory period were performed in attempt to induce VT. If electric stimulation from the right ventricle apex failed to induce VT, stimulation was repeated from the right ventricular outflow tract followed by the LV. We attempted to map all hemodynamically tolerated monomorphic VTs. Unfractionated heparin was administered throughout the procedure to maintain an activated clotting time of 250 to 350 s.
Comparison of Pacing Output Threshold
Pacing from areas of low voltage often requires high output to capture or results in complete lack of capture. This can limit the accuracy of pace mapping and overdrive pacing during tachycardia. Because smaller electrodes have higher electric current density, we hypothesized that 1-mm electrode catheters have lower pacing threshold. We compared pacing output threshold between the linear and the multielectrode-mapping catheters during sinus rhythm at 10 similar sites (within 5 mm from one another) in the region of low bipolar voltage amplitude ≤1.5 mV. At each site, pacing threshold output was determined for each catheter at fixed pacing output duration of 2 ms. Failure to capture was defined as lack of capture at 10 mA at 2 ms.

VT Mapping and Radiofrequency Ablation
Mapping of sustained monomorphic reentrant VTs were performed using activation and entrainment mapping as hemodynamically tolerated. Mapping was attempted using the multielectrode catheter. At areas of diastolic activity, overdrive pacing a cycle length of 10–25 ms shorter than the tachycardia was performed. If pacing captured the tachycardia circuit with concealed fusion, the postpacing interval as well as the S-QRS were analyzed to determine whether the site was in the circuit using conventional criteria. Specifically, a pacing site demonstrating concealed fusion on 12-lead ECG, postspacing interval–tachycardia cycle length (TCL) ≤30 ms, and S-QRS ≤70% TCL was considered within the reentrant circuit. A pacing site demonstrating manifest fusion, postspacing interval-TCL ≤30 ms and S-QRS ≤70% TCL was also considered within the reentrant circuit (outer loop).

To preserve LV structure for histological examination, we avoided ablation in the first 9 postinfarction swine and allowed ablation only in the last 2 swine. In these cases, the linear catheter was positioned at the site of interest (diastolic pathway as determined by the 1-mm multielectrode-mapping catheter), and radiofrequency ablation was performed using energy of 20 to 40 W.

Histopathologic Analysis
After completion of the mapping procedures, animals were euthanized, and the heart was harvested and placed in a 10% buffered formalin solution for >72 hours for tissue fixation. After tissue fixation, the hearts were serially sectioned parallel to the atrioventricular groove into 1-cm thick slices. The tissue samples were paraffin embedded and sectioned at 5-μm thickness perpendicular to the epicardial surface so that each section showed the full thickness of the ventricular wall from epicardium to endocardium. Slides at intervals of 100 μm were stained with hematoxylin and eosin stain as well as with Masson trichrome stain for collagen. Slides were digitized using a Philips UFS slide scanner, and the whole-slide images were displayed via https://slide-atlas.org, a high performance web-based viewer platform. Aligned whole-slide images were displayed side by side. Regions of low voltage were compared simultaneously in adjacent sections allowing characterization of myocardial fibrosis and surviving myofibers.

Statistical Analysis
Descriptive statistics are reported as mean±SD for continuous variables and as absolute frequencies and percentages for categorical
variables. Normality of the continuous variables distributions was assessed using 1 sample Kolmogorov–Smirnov test, and comparisons between the linear and multielectrode-mapping data were performed using the unpaired Student t test or Mann–Whitney U test as appropriate. Categorical variables were compared using the Fisher exact test. Comparison of linear and multielectrode catheter low-voltage areas in the 11 postinfarct swine was performed using the Wilcoxon signed-rank test. A P value of <0.05 was considered statistically significant. Statistical analyses were performed with Stata/MP version 13 (StataCorp, College Station, TX).

Results

Mapping Density and Time
In the 3 healthy swine with structurally normal LV, the number of electrograms acquired with the multielectrode-mapping catheter was significantly greater than that obtained with the linear catheter (986±276 [median 1220] versus 462±216 [median 446]; P<0.01). Similarly, in the postinfarct swine, mapping density was higher with the multielectrode-mapping catheter (1666±1115 [median 1111] versus 483±258 [median 534]; P=0.003). The mapping time was typically shorter using multielectrode-mapping catheters (71±32 minutes [median 69] versus 87±35 minutes [median 86]; P=0.06). This is likely because each beat acquired with the multielectrode-mapping catheter can record ≤10 simultaneous bipolar electrograms compared with only 1 bipolar electrogram recorded with a linear catheter.

Electrogram Characteristics in the Healthy Ventricle
Voltage amplitude and electrogram duration in healthy ventricular tissue were determined in 3 normal swine with structurally normal LVs and during sinus rhythm. A total of 801 electrograms were recorded with the linear catheter and a total of 1831 with the multielectrode-mapping catheter. The mean bipolar electrogram amplitude was similar between the linear and the multielectrode-mapping catheters (4.2±2.3 mV [median 3.7] versus 3.8±2.4 mV [median 3.1]; P=0.36). The 5th percentile of the normal bipolar voltage distribution was also similar between the linear and multielectrode-mapping catheters (1.61 and 1.48 mV, respectively). Using these data, we defined the normal LV endocardial bipolar voltage amplitude as ≥1.5 mV and similar between both catheters.

Electrogram duration during sinus rhythm was shorter with multielectrode-mapping catheters. The mean bipolar electrogram duration was 52±9 ms (median 52 ms) and 95% of all electrograms had a duration of <69 ms. In comparison, mean electrogram duration with linear catheters was 78±12 ms (median 78 ms) and 95% of all electrograms had a duration of <98 ms with the linear catheter (Figure 2).

Electrogram Characteristics in the Scarred Ventricle
We compared the distribution of low bipolar voltage (<1.5 mV) in 11 swine with healed myocardial infarction. The area of low bipolar voltage was 22.5% smaller with multielectrode-mapping catheters when compared with linear catheters (21.7 cm² [median, 19.5; range, 7.8–63.0 cm²] versus 28.0 cm² [median, 23.6; range, 11.4–67.9 cm²]; P=0.003). The area of very low bipolar voltage (conventionally defined as ≤0.5 mV) was 47% smaller with multielectrode-mapping catheters than with linear catheters.

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Figure 2. Electroanatomical mapping (EAM) of healthy ventricular tissue: comparison between linear and multielectrode catheters. Left, EAM map of a normal left ventricle (LV) using a linear catheter (Smart-Touch Thermocool). Right, EAM of the same LV performed immediately afterward using a multielectrode-mapping catheter (Pentaray). The maps are showed in an anterior–posterior projection and with a bipolar voltage range of 0.5 to 1.5 mV. The bipolar voltage amplitude was similar between the 2 maps with 95% of all electrograms ≥1.5 mV. However, electrogram duration was shorter using the multielectrode-mapping catheter. The shorter electrogram duration is because of the smaller interelectrode spacing that results in shorter conduction time between the proximal and distal electrodes.
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The average, median, lower 25th and upper 75th percentiles of low bipolar voltage area for each catheter are detailed in Table. In addition, both linear and multielectrode-mapping catheter bipolar low voltage area measurements aggregated by individual case is available in Figure II in the Data Supplement.

Although mapping low-voltage areas with multielectrode catheters resulted in an overall increased bipolar voltage amplitude, in only 7 of 11 pairs (63%) this resulted in identification of channels. In these cases, maps created with multielectrode-mapping catheters showed heterogeneity within the infarct zone with areas of increased voltage amplitude, whereas maps made with linear catheters showed homogenous area of low voltage (Figure 4A and 4B).

Comparison of electrograms at similar locations (<2 mm) showed that electrograms recorded with linear catheters were more fractionated (95% versus 67%; \( P=0.001 \)) and of longer duration (97±19 ms [median, 93 ms; range, 66–162 ms] versus 73±15 ms [median, 72 ms; range, 49–120 ms]; \( P=0.001 \)).

In 4 of 11 swine (37%), voltage maps made with linear and multielectrode catheters were nearly similar (Figure 4C). In these cases, the mean bipolar voltage amplitude within the low-voltage area was similar between maps made with linear and multielectrode catheters (0.59±0.30 mV [median, 0.56] versus 0.58±0.37 mV [median, 0.50]; \( P=0.56 \)). The presence and extent of electrogram fractionation was similar between linear and multielectrode catheters (93% versus 90%; \( P=0.67 \) and 7.2±1.7 deflections [median 7] versus 7.6±1.8 deflections [median 8]; \( P=0.43 \), respectively).

**Correlation Between EAM and CMR**

All 11 swine with healed anterior myocardial infarction showed a large area of late gadolinium enhancement at the anterior septum, consistent with anterior wall infarction. The distribution of the scar was complex with areas of transmural infarction along with areas of near transmural infarction with either subendocardial or subepicardial (right ventricular) myocardial tissue preservation. The percentage of scar volume measured with CMR (11.2±4.5% [median 12.0%]) was smaller than the corresponding EAM zone of bipolar voltage amplitude ≤1.5 mV when measured with both the linear (15.2±7.1% [median 12.4%]) and the multielectrode (12.±5.9% [median 10.8%]) catheters, but did not reach statistical significance (\( P=0.49 \) and 0.61, respectively). The 7 swine that showed significant differences between maps made with linear and multielectrode-mapping catheters were all

### Table. Comparison of Linear and Multielectrode Catheter in Low-Voltage Areas

<table>
<thead>
<tr>
<th></th>
<th>Linear</th>
<th>Multielectrode</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total acquired electrograms</td>
<td>483±258</td>
<td>1666±1115</td>
<td>0.003</td>
</tr>
<tr>
<td>Bipolar voltage area ≤1.5 mV, cm²</td>
<td>28.0±15.9</td>
<td>19.4, 32.9 (23.6)</td>
<td>21.7±15.4</td>
</tr>
<tr>
<td>Bipolar voltage area ≤1.0 mV, cm²</td>
<td>24.1±15.1</td>
<td>16.9, 28.2 (18.4)</td>
<td>15.5±11.5</td>
</tr>
<tr>
<td>Bipolar voltage area ≤0.5 mV, cm²</td>
<td>15.3±13.7</td>
<td>7.1, 16.7 (10.5)</td>
<td>7.1±5.9</td>
</tr>
</tbody>
</table>

Values expressed as mean±SD; 25%, 75% percentiles (median).

The mean bipolar voltage amplitude within the low-voltage area was higher with multielectrode-mapping catheters when compared with linear catheters (0.99±1.02 mV versus 0.57±0.38 mV; \( P<0.001 \); Figure 3A). The mean bipolar voltage distribution within this area of very low voltage was also significantly higher with multielectrode-mapping catheters compared with linear catheters (0.72±0.81 mV versus 0.30±0.12 mV; \( P<0.001 \); Figure 3B).

Figure 3. Comparison of bipolar voltage amplitude between linear and multielectrode-mapping catheters in the postinfarct zone. A, Bipolar voltage amplitude distribution within the low-voltage area defined as ≤1.5 mV using the linear catheter. Mapping with multielectrode catheters recorded a significantly higher voltage at a similar catheter position (\( P<0.001 \)). B, Comparison of bipolar voltage within the area of very low voltage (dense scar) defined as ≤0.5 mV using the linear catheter. The multielectrode catheter recorded a significantly higher bipolar voltage amplitude at a similar catheter position (\( P<0.001 \)).

(7.1 cm² [median, 5.2; range, 1.3–21.3 cm²] versus 15.2 cm² [median, 10.5; range, 4.4–52.2 cm²]; \( P=0.003 \)). The average, median, lower 25th and upper 75th percentiles of low bipolar voltage area for each catheter are detailed in Table. In addition, both linear and multielectrode-mapping catheter bipolar low voltage area measurements aggregated by individual case is available in Figure II in the Data Supplement.
Figure 4. Electroanatomic maps (EAMs) of the left ventricle in 3 representative examples of postinfarction swine. For each example, the EAM made with the linear catheter is shown on the left, whereas the EAM made with the multielectrode catheter is shown on the right. The maps are displayed in the anterior–posterior view and with a bipolar voltage range of 0.5 to 1.5 mV. In 7 of 11 swine, the mapping resolution within the area of low voltage significantly diverged, whereas mapping with a linear catheter demonstrated homogenous and confluent low-voltage area, mapping with a multielectrode catheter revealed areas channels of normal bipolar voltage amplitude and electrogram characteristics within the low-voltage zone (swine 1 and 2). In 4 of 11 swine, mapping with both catheters demonstrated a confluent area of low voltage that was similar between the catheters (swine 3).
characterized by a nearly transmural scar with evidence of subendocardial myocardial tissue preservation (Figure 5A).

In contrast, the 4 swine with similar voltage maps made with linear and multielectrode-mapping catheters showed either a transmural scar or a scar limited to the subepicardium (Figure 5B). In these cases, the tissue in proximity to the recording catheter was homogeneous, either healthy or scarred myocardium. This data suggest that small multielectrode-mapping catheters have increased resolution to detect heterogeneity within low-voltage tissue that is in close proximity to the recording electrodes (ie, survived subendocardial bundles in post infarction scar).

**Figure 5.** Relationship between late gadolinium enhancement (LGE) and bipolar voltage amplitude recorded with linear and multielectrode-mapping catheters. A, LGE in the anterior septum extending from the left ventricle (LV) to the right ventricle (RV). The arrows are pointed to an area of preserved subendocardial myocardium. The multielectrode-mapping catheter with its small and closely spaced multielectrodes was largely influenced by the closer layer of surviving subendocardial myocardium and recorded a normal or near-normal bipolar voltage amplitude (+++). In contrast, the linear catheter with its larger electrodes and longer interelectrode spacing recorded data representative of a larger field of view containing the thin layer of surviving subendocardial tissue; however, this was overwhelmed by the thicker layer of scar, thus resulting in a low bipolar voltage (+). B, An example of limited subepicardial (RV) scar with normal LV sub and midmyocardial tissue. In these cases, both catheters recorded a normal or nearly normal bipolar voltage amplitude (+++).

**Figure 6.** Relationship between histology and bipolar voltage amplitude recorded with linear and multielectrode-mapping catheters. **Left,** Section of an infarcted anterior left ventricular wall made perpendicular to the fiber direction, displaying the tissue from its endocardial (ENDO) to epicardial (EPI) layer. A narrow layer of subendocardial surviving muscle with a deeper layer of collagen (blue stain). In these areas, the multielectrode-mapping catheter recorded normal or nearly normal bipolar voltage amplitude (+++), whereas the linear catheter recorded low bipolar voltage amplitude (+). **Right,** Section of transmural infarction without surviving myocardium (the subendocardial layer in red are red blood cells). In these areas, both catheters recorded low bipolar voltage amplitude (+). Histological preparation with mason-trichrome staining (x5).
Correlation Between Bipolar Voltage Maps and Histology
Histological analysis was consistent with the CMR analysis, showing complex scar architecture at the anterior septum with areas of transmural infarction along with areas of near transmural infarction with either subendocardial or subepicardial myocardial tissue preservation. Consistent with the CMR data, in the 7 of 11 swine that showed significant differences between maps made with linear and multielectrode catheters, a thin layer of surviving myocardium bundles was identified in the subendocardium (Figure 157x204A). In the 4 swine with similar maps between the catheters, the tissue layers in proximity to the recording catheter (endocardium) were homogeneous showing either a thick layer of myocardium or collagen (Figure 254x169B).

VT Mapping
A total of 10 sustained monomorphic VT were induced in 6 of the 11 postinfarction swine. In 8 of the 10 VTs, the arrhythmia was stable enough to allow positioning of the multielectrode-mapping catheter at channels of increased voltage amplitude as detected by the multielectrode-mapping catheter but not by the linear catheter. In all cases, the recording electrograms were triphasic and narrow, consistent with electrograms recorded during sinus rhythm. In addition, these electrograms occurred during diastole and showed a pattern of sequential activation consistent with propagation through the channel (Figure 7). In 2 hemodynamically tolerated VTs, entrainment from a channel detected with the multielectrode catheter but not with the linear catheter demonstrated an isthmus site. Ablation at this resulted in rapid termination of the VT. Importantly, when the linear catheter was placed at these channels of diastolic activity as recorded with the multielectrode catheter, low voltage, fractionated electrograms were recorded (Figure 8).

LV Pacing Threshold
We compared the pacing threshold between the catheters at areas of low voltage (<1.5 mV) during sinus rhythm. The occurrence of pacing with capture was similar between the multielectrode- and linear mapping catheters (100% versus 96%; P=0.86). However, the pacing threshold was significantly lower with the multielectrode-mapping catheter (0.9±1.3 mV [median, 0.5; range, 0.2–1.8 mV] versus 3.8±3.7 mV [median, 2.7; range, 0.2–10.0 mV]; P=0.001).

Discussion
Major Findings
This study established the voltage distribution and electrogram characteristics of multielectrode-mapping catheters...
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In addition, it compared the mapping resolution between standard linear (Thermocool) and multielectrode (Pentaray) catheters within scar tissue during sinus rhythm and VT using EAM, CMR, and histology.

The major findings are as follows:

1. Bipolar voltage amplitude in the healthy ventricle is similar between linear and multielectrode catheters with a 5th percentile of ≈1.5 mV.
2. Mapping resolution within areas of low voltage and scar is enhanced with multielectrode catheters, identifying areas of preserved myocardial bundles (channels), otherwise considered dense scar by standard linear catheters.
3. Multielectrode catheters are advantageous for mapping scar-related reentrant VT because their small and closely spaced electrodes allow identification of distinct diastolic activity (including diastolic pathways) that may not be seen with standard linear catheters.
4. Multielectrode catheters allow pacing with capture of low-voltage tissue at lower output than linear catheters.

Three-dimensional EAM systems had been developed to assist with mapping and ablation of cardiac arrhythmias. These systems have become an essential tool for mapping scar-related VT and are frequently used to evaluate the underlying substrate of scar-related VTs. They are valuable for identifying the anatomy of the substrate and for guiding ablation procedures. However, the challenge remains in accurately characterizing the complex and heterogeneous nature of scar tissue.

Figure 8. Difference in electrogram amplitude between multielectrode and linear catheters. Both the linear and the multielectrode catheters were placed at a site with diastolic electric activity during ventricular tachycardia. Although the multielectrode catheter recorded narrow electrograms with near-normal bipolar voltage amplitude (0.62–1.42 mV), the linear catheter, placed at similar position and with a tissue contact force of 15 g recorded a fractionated very low amplitude signal (0.08 mV).

(Pentaray) in the ventricle of normal and postinfarction swine. In addition, it compared the mapping resolution between standard linear (Thermocool) and multielectrode (Pentaray) catheters within scar tissue during sinus rhythm and VT using EAM, CMR, and histology.

The major findings are as follows:

1. Bipolar voltage amplitude in the healthy ventricle is similar between linear and multielectrode catheters with a 5th percentile of ≈1.5 mV.
2. Mapping resolution within areas of low voltage and scar is enhanced with multielectrode catheters, identifying areas of preserved myocardial bundles (channels), otherwise considered dense scar by standard linear catheters.
3. Multielectrode catheters are advantageous for mapping scar-related reentrant VT because their small and closely spaced electrodes allow identification of distinct diastolic activity (including diastolic pathways) that may not be seen with standard linear catheters.
4. Multielectrode catheters allow pacing with capture of low-voltage tissue at lower output than linear catheters.

Three-dimensional EAM systems had been developed to assist with mapping and ablation of cardiac arrhythmias. These systems have become an essential tool for mapping scar-related VT and are frequently used to evaluate the underlying substrate of scar-related VTs. However, evaluation of the substrate using standard mapping techniques is mystified by assumptions and misconceptions. Specifically, bipolar voltage is a measure of conduction time between 2 electrodes, rather than a measure of the underlying tissue (healthy versus scar). It is influenced by multiple variables including electrode size, interelectrode spacing, angle of incidence (catheter orientation relative to the surface), the vector of wave propagation, and filtering. Their combined effect is associated with significant variations in the recorded bipolar voltage amplitude at any single recording point. Bipolar voltage recorded with standard catheters can differentiate dense scar (<0.1 mV) from healthy myocardium (1.55 mV); however, they have insufficient sensitivity to characterize the architecture of a complex and heterogeneous scar tissue.

The notion that electrode size and interelectrode spacing characteristics affect bipolar signal morphology, and spatial resolution is not a new concept. Schaefer et al demonstrated in 1951 the mathematical relationship between electrode distance from the recording source (ie, tissue) and the implications of unipolar and bipolar electrogram characteristics. This initial work also introduced the concept that bipolar electrodes reduce far-field contamination, and this effect was maximized as interelectrode distance decreased. Durrer et al validated this concept in 1957 in a canine LV experimental model. In more recent work, Stinnett-Donnelly et al showed using computational and in-vitro models that resolution is affected by electrode size, interelectrode spacing, and distance from the source.

Multielectrode-mapping catheters have smaller electrodes and closer center-to-center interelectrode spacing in
comparison with conventional linear mapping catheters. This results in increased mapping resolution because each data point represents electric activity from a smaller tissue size. This may allow to identify surviving myocardial bundles channels within an area of heterogeneous scar, that potentially would be contaminated by surrounding fibrosis with the large distal electrode of the linear catheter. In addition, mapping with multielectrode catheters also contain more data points, and points acquired with increased variability in the angle of incidence and the relationship to the vector of propagation. They are therefore less subjective to the individual confounding effects of bipolar voltage amplitude measurement. As such, we hypothesized that the small and closely spaced multielectrodes would provide enhanced detection of the relatively thin layer of surviving subendocardial tissue versus the linear catheter with its larger electrodes and longer interelectrode spacing recorded data representing a larger field of view containing the thin layer of surviving subendocardial tissue as well as the adjacent layers of scar, thus resulting in a low-voltage and fractionated electrogams.

Tung et al performed endocardial and epicardial LV mapping of an ischemia-reperfusion swine model with both a linear 4-mm electrode catheter using a Carto mapping system and a 2-mm duo-decapolar catheter using a NAVX system. Similarly to our observation, multipolar electrode catheters resulted in higher mapping density and a 29% smaller low-voltage area. They also reported higher prevalence of late potentials using multielectrode catheters. Although this is logical because of increased sampling and higher mapping resolution, we did not find statistical difference in late potential prevalence. This might be because of lower prevalence of late potentials in our post–left anterior descending infarct model.

Berte et al performed LV mapping with the 3.5-mm electrode catheter (Navistar) and multielectrode-mapping catheter (Penatary) in both postinfarction sheep and patients with scar-related VT. They also reported increased mapping density and higher prevalence of late abnormal ventricular activation using multielectrode-mapping catheters. However, they reported increased bipolar low-voltage area with multielectrode catheters compared with linear 3.5-mm electrode catheters. This difference may be related to inadequate tissue contact when mapping with multielectrode catheters. Furthermore, they did not compare the low-voltage area with CMR and histopathology, precluding objective assessment of the true scar.

We have recently shown that multielectrode-mapping catheters with small and closely spaced electrodes (Pentaray) have significant advantages for mapping scar-related atrial arrhythmias in human. When compared with linear mapping catheter (Thermocool), multielectrode-mapping catheters were able to identify surviving myocardial bundles that participated in the scar-related atrial arrhythmia, facilitating successful ablation.

In this study, we performed prospective comparison between 2 commercially available catheters: a standard linear catheter (Smart-Touch Thermocool) and a 1-mm multielectrode-mapping catheter (Pentaray). We established the normal voltage distribution and electrogram characteristics of multielectrode-mapping catheters in the healthy LV. The cutoff of normal bipolar voltage amplitude was similar to standard linear catheters =1.5 mV. However, electrogram duration was significantly shorter (52±9 ms versus 78±12 ms; P=0.001). This is because of the shorter interelectrode spacing and shorter conduction time between the 2 electrodes.

Although multielectrode catheters have increased mapping resolution, it had little value in normal healthy myocardium as bipolar voltage variation between 1.5 and 5 mV represent normal myocardium. In contrast, such voltage variations in the infarct and peri-infarct zone determined the feasibility to identify subendocardial surviving myocardial bundles that formed conduction channels during sinus rhythm and during VT (isthmuses). We found that the improved mapping resolution of multielectrode catheter was most significant in areas of heterogeneous scar distribution and in close proximity to the recording catheter. In these areas, the small and closely spaced multielectrodes are subjected to lesser tissue averaging effects, allowing detection of surviving myocardial bundles within an area of heterogeneous scar. Finally, the pacing output threshold of multielectrode-mapping catheters within low-voltage areas is lower because of increased electric current density at the electrode–tissue interface. This may be advantageous for pace or entrainment mapping.

Study Limitations
This preclinical study was performed in swine and used an established, human-like model of chronic anterior myocardial infarction. Although bipolar voltage amplitude in healthy and scar tissue are similar between swine and human, this has not been validated for 1-mm electrode catheters. However, our limited experience in human with postinfarction VT is consistent with findings of this study, showing improved mapping resolution with ability to identify surviving myocardial bundles with multielectrode catheters. The increased resolution of multielectrode-mapping catheters seems to be confined to the tissue layers adjacent to the recording catheter (endocardium and subendocardium). Identification of these regions may, in part, be because of increased mapping density acquired with the multielectrode catheter. Although this may be beneficial for patients with healed myocardium infarction and subendocardial scar, its potential in other substrates, in particular patients with nonischemic cardiomyopathy with midmyocardial and subepicardial scar is not clear. Although we compared pacing threshold between catheters at sites within 5 mm, this may not be indicative of actual similar tissue. We also did not compare differences in unipolar voltage amplitude. Although this may be an interesting measure, smaller electrodes have smaller field of view and may, therefore, be less sensitive to measure effects of remote tissue layers. Finally, we did not account for signal decay during electrogram duration measurements for both the linear and the multielectrode catheters.

Conclusions
Multielectrode catheters have increased mapping resolution, that is particularly beneficial at the low-voltage area. It allows identifying surviving myocardial bundles channels, otherwise considered dense scar by standard linear catheters. This technique may improve mapping and ablation of postinfarction VTs.
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Supplemental Material

Supplemental Figure 1:

Method for electrogram comparison between multielectrode and linear catheters. The XYZ location data of each data point obtained with both catheters were exported. In-house MatLab based algorithm was developed to calculate the distance between points. Data points within ≤2mm from each other were used for comparison.
Supplemental Figure 2:

Linear and multielectrode bipolar low voltage area measurements for each individual swine.

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<th>Bipolar Voltage Area ≤1.0mV (cm²)</th>
<th>Bipolar Voltage Area ≤1.5mV (cm²)</th>
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