Utility of high-resolution electroanatomic mapping of the left ventricle using a multispline basket catheter in a swine model of chronic myocardial infarction

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BACKGROUND Standard electroanatomic mapping systems use a single catheter to perform left ventricular substrate mapping. A new mapping system uses a 64-electrode mini-basket catheter to perform rapid automated acquisition of chamber geometry, voltage, and activation.

OBJECTIVE The aim of this study was to compare the accuracy of electroanatomic mapping using the basket catheter with that of mapping using a standard linear catheter in a swine model of chronic myocardial infarction.

METHODS Ten swine underwent left anterior descending coronary artery occlusion to create an anteroseptal myocardial infarction. Animals underwent delayed-enhancement magnetic resonance imaging (MRI) and then detailed left ventricular voltage mapping with both the basket and the linear catheter. Map characteristics and scar area were compared between the basket catheter, linear catheter, and MRI. Induced ventricular tachycardia (VT) was mapped with the basket catheter.

RESULTS More points were acquired with the basket catheter than with the standard catheter (8762 ± 3164 vs 1712 ± 551; P < .001). The fifth percentile of normal bipolar voltage distribution with the basket catheter was 1.54 mV. Using a bipolar voltage cutoff of 1.5 mV, the total infarct areas measured using the basket catheter, linear catheter, and MRI were similar (17.8 cm² vs 20.9 cm² vs 17.5 cm²; P = .69); however, the correlation between MRI and catheter scar area measurement was best for the basket catheter (basket vs linear: r = .76 vs r = .71). In 3 animals, sustained poorly tolerated VT was initiated and the circuit mapped successfully with the basket catheter in < 5 minutes.

CONCLUSION Rapid substrate and activation mapping using a 64-electrode mini-basket catheter allows detailed voltage and activation mapping in postinfarction cardiomyopathy. This system may be useful for substrate and VT mapping in human postinfarction cardiomyopathy.

KEYWORDS Electroanatomic map; Late potential; Ventricular tachycardia; Myocardial infarction; MRI

ABBREVIATIONS 3D = 3-dimensional; FWHM = full-width at half-maximum; ILP = isolated late potential; LV = left ventricle/ventricular; MI = myocardial infarction; MRI = magnetic resonance imaging; RV = right ventricle/ventricular; VT = ventricular tachycardia

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Introduction

The 3-dimensional (3D) electroanatomic mapping systems have been developed to assist with mapping and ablation of cardiac arrhythmias.1–4 These systems have become an essential tool for the mapping and treatment of complex arrhythmias. Substrate map-guided ablation in patients with hemodynamically unstable ventricular tachycardia (VT) relies on the delineation of myocardial scar by electroanatomic voltage mapping. However, acquiring a high-density voltage map using a single or a small number of electrodes on a roving catheter is labor-intensive and time-consuming. In addition, mapping during induced poorly tolerated VT is often not performed because hemodynamic instability precludes the lengthy time needed to acquire an activation map. While substrate mapping during sinus rhythm allows empirical ablation of VT exit sites and regions of slow conduction, the results remain suboptimal.5

The use of a multielectrode basket catheter with automated point annotation may allow acquisition of rapid left ventricular (LV) substrate maps during sinus rhythm and VT. However, the optimal voltage cutoffs to identify scar and the accuracy of scar delineation have not been validated. The purpose of this study was to determine the ideal voltage cutoff and the accuracy of scar delineation with the basket...
A catheter compared to the linear catheter in a swine model of chronic myocardial infarction (MI).

Methods

Animal preparation

This study was approved and monitored by the Laboratory Animal Resource Center at the University of California, San Francisco, according to the American Heart Association guidelines for animal research protocol. Ten swine weighing approximately 25–35 kg were used for the study. In each procedure, after a 12-hour fast, anesthesia was induced with an intramuscular injection of ketamine and acepromazine. General anesthesia was maintained by inhalation of 1%–5% isoflurane, and each animal was mechanically ventilated with 100% oxygen. Internal jugular venous, femoral venous, and femoral arterial access was obtained by percutaneous puncture using the modified Seldinger technique.

Porcine chronic infarct model

Swine first underwent a percutaneous MI using transient balloon occlusion of the mid-left anterior descending coronary artery guided by fluoroscopy.

Amiodarone (400 mg orally daily) was administered for 1 week before the infarct procedure. Lidocaine 100 mg bolus intravenous injection and 1 mg/min drip were administered before the infarct procedure. Additional lidocaine boluses were given when frequent ectopy or nonsustained VT occurred. Sustained pulseless VT or ventricular fibrillation was treated with prompt external direct current shock. Under general anesthesia, angiography of the left coronary artery was performed using a 7-F hockey-stick guide catheter. A wire was advanced to the distal left anterior descending coronary artery, and a noncompliant angioplasty balloon of appropriate size (diameter 2.5–3.5 mm; length 10–20 mm) was inflated just past the first diagonal branch. Balloon occlusion was confirmed by documenting the complete absence of coronary blood flow distal to the balloon with angiography. Balloon inflation was maintained for 90 minutes. At the completion of the infarct procedure, the balloon was deflated and removed along with the wire and the guiding catheter. The animals were recovered and survived for approximately 4 weeks.

Magnetic resonance imaging acquisition

To assess the infarct size, magnetic resonance imaging (MRI) was performed using 1.5-T scanner (Philips Achieva, Cleveland, OH), 3–4 weeks after the infarct procedure. All imaging was performed with a 5-channel cardiac coil. Ventilator breath-holding was used to limit respiratory motion, and electrocardiographic gating was used to synchronize image acquisition. After obtaining scout views, cine MRI acquisitions were performed using steady-state free precession imaging (field of view 28 cm; slice thickness 10 mm; matrix 288; Repetition Time (TR)/Echo Time (TE)/flip 3.7 ms/1.8 ms/70°; 16 heart phases) in the long-axis (2-chamber and 4-chamber views) and short-axis orientation covering the complete LV. Gadolinium contrast (Magnevist, Bayer HealthCare, Whippany, NJ) was then intravenously administered at 0.2 mL/kg and permitted to circulate for 10 minutes before viability imaging. Delayed enhancement viability imaging (field of view 28 cm; slice thickness 1.5 mm; matrix 256; TR/TE/flip 4.6 ms/1.4 ms/15°; inversion delay 200–250 ms [to null normal myocardium]) was also performed with short- and long-axis orientations and was used for infarct characterization.

Image processing

The MRI data were exported to MeVisLab (MeVis Medical Solutions AG, Bremen, Germany), and the contours defining the LV endocardial and epicardial surfaces were traced manually from the cine MRI data. The LV endocardial and epicardial surfaces were reconstructed as triangular meshes by fitting the contours, and the LV wall was defined as the region bounded by the 2 surfaces. Only the pixels within the LV wall were considered in our analysis. Signal intensity was smoothed and projected onto the endocardial surfaces by averaging the signal intensity of all wall pixels in a neighborhood of 5 mm. The MRI signal intensity map was then compared with the electroanatomic voltage map (Figure 1).

Because there is no definitive consensus as to what is the criterion standard for scar determination using MRI, we compared 3 different scar determination methodologies currently used in the literature in a separate study. These methodologies define cutoff thresholds on the basis of the following methods: (1) standard deviations from normal myocardial signal intensity, (2) signal intensity normalized to the maximal signal intensity of the blood pool, and (3) signal intensity normalized to maximum myocardial signal intensity. Among these 3 methods, we found that using signal intensity normalized to the maximum myocardial signal intensity (ie, method 3) with cutoff values of 0.8 (dense scar region) and 0.5 (border zone + dense scar region) were the most reproducible and yielded the best correlation between the MRI and electroanatomic maps. By using a cutoff value of 0.5 to define the border zone + dense scar region, the method of normalizing the signal intensity with the maximum myocardial signal intensity becomes equivalent to the “full-width at half-maximum” (FWHM) method, which is popularly used for scar delineation. In the FWHM method, the infarct region is defined to be the region that contains pixels with signal intensity greater than 50% of a user-selected point inside the hyperenhanced region. The FWHM method was found to be more reproducible than the “standard deviation” method (ie, method 1) in delineating the scar and correlates best with postmortem data. In this study, the MRI total scar and dense scar surface areas were computed using these cutoff thresholds.

Multielectrode mini-basket catheter

The mapping catheter (IntellaMap Orion, Boston Scientific, Natick, MA) has an 8-F shaft with bidirectional deflection and a mini-basket array with 64 electrodes on 8 splines
Figure 1  
A: An example of construction of MRI signal intensity maps. The MRI signal intensity ratio (range 0–1.0; see text) is projected onto the endocardial shell for each slice.  
B: A comparison of the MRI signal intensity maps with the high-resolution voltage maps acquired with the basket catheter is shown in the RAO and inferior projections. MRI = magnetic resonance imaging; RAO = right anterior oblique.

(Figure 2). The low-impedance electrodes have a surface area of 0.4 mm$^2$ and are distributed on 8 splines (A-H) with a 2.5-mm interelectrode spacing. The electrode array can be deployed into a spherical configuration through mechanical flexion of the splines; however, mapping can be performed with the basket catheter in any stage of deployment, from linear to spherical (diameter 3–22 mm). The location of each of the 64 electrodes is identified by a combination of a magnetic sensor in the distal region of the catheter and impedance sensing on each of the 64 electrodes on the basket catheter.

Figure 2  
The novel multielectrode mini-basket catheter. This catheter has an 8-F shaft with bidirectional deflection and a mini-basket array with 64 electrodes.  
A: The electrode array can be deployed into a spherical configuration through mechanical flexion of the splines.  
B: The location of each of the 64 electrodes is identified by a combination of a magnetic sensor in the distal region of the catheter and impedance sensing on each of the 64 electrodes on the basket catheter.
Electroanatomic mapping system
The mini-basket catheter is part of an integrated novel electroanatomic mapping system (Rhythmia, Boston Scientific). This system includes an electronic patient interface unit and a computer workstation. Individual cardiac beats are acquired automatically. In the automatic data acquisition mode, cardiac beats are added to the map on the basis of 4 criteria: (1) the collecting electrode remains in a stable point in space, (2) the cycle length of the cardiac rhythm is stable, (3) the timing of the collecting electrogram relative to the reference electrogram is stable, and (4) the detected beat is within the selected respiratory gating (the respiratory cycle is tracked by measuring impedance change across the chest). The criteria are set by the operator before mapping is begun and can be adjusted, if needed, during mapping. The electrograms are automatically collected and annotated; hence, the map can be created by continuous movement of the catheter in real time, with minimal manual annotation required. The activation timing is measured using the point of maximum amplitude of the bipolar signal or the maximum negative dV/dt of the unipolar signal. This automatic and continuous acquisition system allows one to acquire a large number of points even if a standard linear catheter is used.

The surface geometry of the chamber is continuously constructed by outermost electrode locations associated with accepted beats. The electrograms in the accepted beats are included in the electroanatomic activation map only when the electrode is within 2 mm of the surface geometry, and this process is continuously updated as the surface geometry is acquired. During acquisition of activations and voltages, the software can display specified surface and intracardiac electrograms of each beat. Completeness of each map was determined when the uniform distributions of points were acquired throughout the map, and the morphology was consistent with that of the entire LV. After data acquisition, individual activation in selected point can be reviewed rapidly by sliding a cursor over the map, allowing manual reannotation of activation timing or deletion of points if incorrect.

Electroanatomic mapping and electrophysiology study
Within 1 week of the cardiac MRI, electroanatomic mapping and electrophysiology study were performed. A 6-F quadrriporal catheter was advanced via the femoral vein to the right ventricular (RV) apex for pacing. A 7-F decapolar catheter was inserted via the right jugular vein and positioned in the coronary sinus under fluoroscopic guidance. An 8-F intracardiac echocardiography catheter (ACUSON AcuNav, Siemens Medical Solutions, Mountain View, CA) was advanced to the RV to assist with mapping. A heparin bolus was administered, and the mapping catheter was advanced to the LV via a retrograde aortic approach from the femoral artery. A complete substrate map of the LV was acquired with the basket catheter during sinus rhythm and/or RV apical pacing. The entire LV geometry and voltage map was then reacquired with a steerable quadrripolar linear mapping catheter in the same rhythm and with the same mapping system. We used a quadrripolar linear catheter with a 4-mm-tip electrode and 1.27-mm ring electrodes separated by 2.5–2.5–2.5-mm interelectrode spacing (Blazer II or prototype IntellaTip, Boston Scientific). The electrograms were recorded from both the distal and proximal bipoles of the linear catheter. After detailed LV voltage mapping, an RV voltage map was also obtained using the mini-basket catheter (this map was not repeated with the linear catheter due to time constraints). Finally, programmed stimulation (single, double, and triple extrastimuli at 400-ms drive train) and burst pacing (350–250 ms decrementing by 20 ms between bursts) from the RV apex was performed to induce VT. If monomorphic VT was induced, LV activation mapping was performed with the mini-basket catheter during VT. If VT did not terminate spontaneously after several minutes, direct current cardioversion were performed. In surviving animals, epicardial access was obtained using the percutaneous subxiphoid approach, as described previously. An epicardial voltage map was acquired during sinus rhythm using the basket catheter in an undeployed state. Animals were euthanized at the end of the mapping procedure, and the hearts were excised.

Image registration and reference values for defining abnormal voltage
The voltage map and MRI data were exported into the Visualization Toolkit(VTK; Kitware, Inc, Clifton Park, NY) format for visualization and postprocessing using ParaView 4.0.1 software (Kitware, Inc). The 3D electroanatomic maps were manually registered onto the MRI signal intensity image using the LV apex, inferior edge of mitral annulus, and aortic annulus as the landmarks. After primary registration, surface adjustment was performed to minimize the distance between the electroanatomic map surface and the MRI surface. The regions with voltage <1.5 mV was then traced on the MRI contour. The percent overlap between the electroanatomic map and the MRI map was defined as the percent total surface area with normal voltage and normal MRI signal intensity plus the percent total surface area with low voltage and high MRI signal intensity.

To define the normal electrogram voltage amplitude recorded in the LV endocardium with the basket catheter, we excluded scar regions identified by MRI. After registration of the MRI with the electroanatomic map, the confluent
infarct regions (with normalized signal intensity > 0.5) with a 1-cm border were contoured on the electroanatomic map. We then cut away these scar regions in the 3D electroanatomic maps and determined the voltage distribution of the remaining normal myocardium. The bipolar and unipolar voltage cutoff values were determined from the fifth percentile voltage values obtained from the healthy endocardium. 3D = 3-dimensional; MRI = magnetic resonance imaging.

Late potentials
The electroanatomic maps were analyzed off-line to identify isolated late potentials (ILPs), which were tagged on the electroanatomic voltage map. ILPs were defined as split electrogams, with the second component occurring after the terminal QRS and >20 ms after the end of the local ventricular electrogram.12

Statistical analysis
The values presented are expressed as mean ± SD and range. Tools provided within the electroanatomic mapping system and MRI software allowed the measurement of scar surface area within a user-specified region. A paired Student t test was used to compare continuous data. Discrete variables were compared using the Fisher exact test or $\chi^2$ test, as appropriate. Correlation between groups was measured using Pearson’s product-moment correlation coefficient. A P value of <.05 was considered statistically significant.

Results
Ten swine underwent electroanatomic mapping 33 ± 4 days after MI creation. The endocardial LV electroanatomic mappings were obtained using the basket catheter during sinus rhythm ($n = 5$) or RV pacing ($n = 5$). In 1 swine, ventricular fibrillation occurred after mapping with the basket catheter; mapping with the linear catheter could not be performed. The number of electrogams acquired using the basket catheter was significantly greater than that obtained using the linear catheter (basket vs linear: 8762 ± 3164 points vs 1712 ± 551 points; $P < .001$). The linear catheter electrogams were also “automatically” continuously acquired using the same acquisition system from both the distal and proximal bipoles of the mapping catheter. This explains the large number of points acquired compared to conventional point-by-point mapping using manual electrogram annotation.

In the automated recording software system, a “beat” refers to each recorded QRS complex; therefore, each beat recorded with the basket catheter may contain up to 56 overlapping bipolar and 64 unipolar electrogams. A total of 5052 ± 1666 beats were recorded per animal, and 2876 ± 1113 beats (56.9%) were automatically rejected by the software. Of the included beats, a total of 108,646 ± 45,477 electrogams were recorded per map; 8.1% of the points within 2 mm of the outermost shell were accepted to obtain the final maps. Thus, 56.9% of the QRS complexes were rejected before acquisition, and then 91.9% of the accepted points were rejected by the system as internal to the geometry.

All 10 swine had evidence of scar in the anteroseptal wall of the LV on the late gadolinium-enhanced MRI images. The mean infarct area measured by MRI was 17.4 ± 7.4 cm² and varied from 10.0 to 30.4 cm² (Table 1).

Normal voltage cutoffs
A total of 30,325 points were recorded in the 10 animals from normal endocardial regions using the basket catheter.

### Table 1 Comparison of scar surface area

<table>
<thead>
<tr>
<th></th>
<th>Basket catheter</th>
<th>Linear catheter</th>
<th>MRI</th>
<th>$P$ (basket catheter vs linear catheter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total scar area (cm²)</td>
<td>17.8 ± 8.7</td>
<td>20.9 ± 10.5</td>
<td>17.4 ± 7.4</td>
<td>.005</td>
</tr>
<tr>
<td>Border zone area (cm²)</td>
<td>11.4 ± 5.9</td>
<td>15.5 ± 4.2</td>
<td>15.3 ± 6.4</td>
<td>.017</td>
</tr>
<tr>
<td>Dense scar area (cm²)</td>
<td>6.4 ± 4.9</td>
<td>5.4 ± 8.1</td>
<td>2.2 ± 2.3</td>
<td>.97</td>
</tr>
<tr>
<td>Total EGMs</td>
<td>8762 ± 3164</td>
<td>1712 ± 551</td>
<td></td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

EGM = electrogram; MRI = magnetic resonance imaging.
The mean bipolar electrogram amplitude recorded from the normal area in the LV was 5.3 ± 3.8 mV. The fifth percentile of normal bipolar voltage distribution using the basket catheter was 1.54 mV. Using these data, we defined normal endocardium measured with the basket catheter as a bipolar electrogram voltage cutoff of >1.5 mV. On the basis of a previous study on catheter and intraoperative mapping, we then designated a value of <0.5 mV corresponding to dense scar. The mean unipolar electrogram amplitude recorded with the basket catheter in the normal LV area was 8.1 ± 3.1 mV; the fifth percentile of normal unipolar voltage distribution was 4.11 mV. Therefore, the abnormal LV unipolar signal amplitude was defined as <4.0 mV.

Electroanatomic voltage mapping

Confluent low-voltage (<1.5 mV) areas were seen in the maps created with the basket and linear catheters in all 10 swine (Figure 4). The LV endocardium total scar area measured using the basket catheter was smaller than that measured using the linear catheter (basket vs linear: 17.8 ± 8.7 cm² vs 20.9 ± 10.5 cm²; P = .0054; Table 1), likely owing to less interpolation between normal and low-voltage points. There was no significant difference in the mean surface area of the dense scar (basket vs linear: 6.4 ± 4.9 cm² vs 5.4 ± 8.1 cm²; P = .97). Therefore, the border zone measured using the basket catheter was smaller than that measured using the linear catheter (basket vs linear: 11.4 ± 5.9 cm² vs 15.5 ± 4.2 cm²; P = .017). The correlation between MRI and catheter scar area measurement was best for mapping with the basket catheter (basket vs linear: r = .76 vs r = .71). The % overlap of scar and normal myocardium between the MRI and electroanatomic maps was also higher for the map created with the basket catheter (basket vs linear: 82.9% vs 79.4%; P < .0001).

ILPs were identified in 7 LV maps using the basket catheter and 5 LV maps using the linear catheter. In 1 swine, ILPs were recorded only using the basket catheter. More ILPs per animal were identified with the basket catheter than with the linear catheter (basket vs linear: 91 ± 63 vs 25 ± 14; P = .036). Comparing the location of ILPs between the maps with basket and linear catheters, we found that ILPs were located in a similar location in the anterior scar area in all 5 swine.

LV activation map during “simulated” VT

Five swine underwent electroanatomic mapping during rapid RV apical pacing (120–140 ppm) in order to “simulate” activation mapping during stable VT. The mean number of acquired points for the activation maps per animal was 8758 ± 4529 points; no editing was required of acquired points. The activation maps indicated septal breakthrough with slow conduction into and around the scar (Figure 5). The mean LV total activation time was 91 ± 23 ms.

RV voltage map

RV electroanatomic maps with the mini-basket catheter were obtained in 9 swine during sinus rhythm. The average number of electrograms per animal was 4405 ± 2113 points. Although every area of the RV was accessible with the multielectrode catheter, it was frequently difficult to obtain

Figure 4  The comparison of voltage maps created with the basket and linear catheters and 3-dimensional signal intensity MRI image in pig 10. The infarct areas measured by basket catheter, linear catheter, and MRI were similar. A: The magnified image of the border zone in the LV map created with the basket catheter. Note the number of points in the border zone. A few points with lower voltage, possibly owing to poor contact (white arrows), are overwhelmed by the number of normal voltage points in the final map. B: Magnified image of the border zone in the LV map created with the linear catheter. The density of points is lower, and the mapping system therefore performs more interpolation between points (white arrows). LV = left ventricular; MRI = magnetic resonance imaging.
adequate catheter contact with the anterior wall because of angulation passing the basket catheter through the tricuspid valve (Figure 6A).

**Epicardial voltage mapping**

Four pigs with stable hemodynamics underwent epicardial voltage mapping using the mini-basket catheter. The operator moved the undeployed mini-basket catheter easily throughout the pericardial space. The mean low-voltage (<1.5 mV) area was 5.7 cm$^2$ (range 2.3–8.1 cm$^2$). The basket catheter was not expanded for epicardial mapping; however, some space was left between each spline (Figure 2). The pericardial space itself is considered another cardiac chamber by the mapping system (Figure 6, B-0). The pericardial-side electrodes acquire far-field electrograms while the epicardial-side electrodes acquire true contact epicardial electrograms. The operator needs to view inside the maps to visualize epicardial voltage information (Figure 6, B-1, white arrow). The outside color map gives the far-field voltage information on the pericardial side (Figure 6, B-2). Acquiring points from the epicardial true LV apex was often limited owing to the configuration of the undeployed basket catheter.

**VT induction and activation mapping**

Sustained monomorphic VT was induced by programmed stimulation in 3 of 10 swine. All 3 VTs were hemodynamically unstable (systolic blood pressure <50 mm Hg). The reentrant circuits of 2 of 3 VTs were completely mapped with the basket catheter in <5 minutes. For example, in pig 7, the voltage map in nominal setting (upper threshold 1.5 mV; lower threshold 0.5 mV) showed a large dense scar area in the anteroseptal wall (Figure 7A). On lowering the lower voltage cutoff, 3 islands with very low voltage appeared. A total of 203 ILPs were identified in the low-voltage area. Most ILPs were identified around channels of relatively preserved voltage (Figure 7B). A sustained poorly tolerated VT at a cycle length of 355 ms was induced with programmed ventricular stimulation. The 12-lead electrocardiogram during VT showed right bundle branch block morphology with superior axis. The negative peak in lead II was selected as a reference; the mapping window duration was set to 335 ms. After quickly mapping the LV (3.5 minutes) with the mini-basket catheter, almost all the tachycardia cycle length was included in the circuit. The VT circuit included a voltage channel with ILPs (Figure 7C). Sinus rhythm was then restored with external defibrillation.

**Safety**

After completion of the electrophysiological study and electroanatomic mapping, the animals were euthanized and the hearts were immediately excised. Autopsy examination of the LV did not reveal any evidence of pericardial bleeding, rupture of any chordae tendineae, hematoma, or perforation.
Discussion

In this preclinical study, we assessed the feasibility of a novel high-density electroanatomic mapping system and an associated multielectrode mini-basket catheter for the mapping of postinfarction ventricular arrhythmias. The main findings of this study are as follows: (1) the mini-basket catheter can create detailed voltage and activation maps of LV postinfarct cardiomyopathy; (2) standard bipolar cutoff values can be used for scar delineation using this system; (3) the mini-basket catheter is able to access the aorta, LV endocardium, and RV epicardium without complications; (4) scar dimensions mapped with the basket catheter correlate well with that determined by cardiac delayed-enhancement MRI.

Several previous animal studies have reported the feasibility of this electroanatomic mapping system and basket catheter. In these animal studies, it was demonstrated that the mini-basket catheter could acquire high-resolution electroanatomic maps rapidly.\textsuperscript{13,14} Nakagawa et al\textsuperscript{13} created a canine right atrial linear lesion model to test whether this system could depict a complex activation pattern in the atrium. They demonstrated that this system could create geometry and localize a line of block and electrical gap accurately. However, these studies examined this system for the mapping only in the atrium and normal LV.

In substrate-based ablation, the accurate identification of the low-voltage area is a cornerstone of the ablation of the scar-related VT.\textsuperscript{15–17} However, the conventional electroanatomic mapping technique has some limitations. Point-by-point mapping using a single or small number of electrodes on a catheter can be time-consuming and labor-intensive. Another limitation of this approach is that electroanatomic mapping with a linear catheter may characterize normal areas as scar due to far-field recording or poor catheter contact. In the present study, software allowing automatic data acquisition acquired a large number of electrograms even using the linear catheter (mean 1712 ± 551 points). Despite this, the simultaneous collection of electroanatomic data from a large number of electrodes of the mini-basket catheter led to the creation of even more detailed maps (8762 ± 3164 points). This ultra–high-density mapping represented sharp demarcations between the abnormal myocardium and normal area. The total scar area mapped with the mini-basket catheter was smaller and had better correlation with MRI as compared with the linear catheter. There are several possible explanations for why the scar area mapped with the basket catheter was smaller. In the lower-density maps created with the linear catheter, the mapping system automatically color codes the region between scar and normal myocardium (Figure 4), potentially overestimating the size of the border.
As a result, the total scar area may be larger in the maps created with the linear catheter. Another possible mechanism is a greater impact of the points with poor contact force. If there is an isolated point with poor contact force (Figure 4B, white arrow) in the lower-density maps, the system misidentifies the area around the point as scar. In the maps created with the basket catheter, the high density of points limits the contribution of any single point with poor contact (Figure 4A, white arrows).

Marchlinski et al distinguished abnormal myocardium in patients with cardiomyopathy from normal myocardium in healthy controls by using an endocardial voltage cutoff of $<1.5$ mV. This cutoff value was subsequently validated in a porcine infarct model to identify transmural scar. Consistent with these observations, a bipolar voltage cutoff of $<1.5$ mV was identified in our animal model. In contrast, there is a broad range (6.2–10 mV) of unipolar voltage cutoffs in chronic animal infarction models. Hutchinson et al identified abnormal epicardium using an endocardial unipolar voltage of $<8.3$ mV in patients with nonischemic cardiomyopathy and normal LV endocardial bipolar voltage. Our unipolar voltage cutoff of 4.0 mV was lower than that in these previous studies.

The difference in the unipolar voltage cutoff in our study may be related to the smaller electrode size of the mini-basket catheter or differences in thickness or voltage characteristics between swine and human myocardium.

The border zone is often an important ablation target that harbors the VT isthmus. With adjustment of the lower voltage cutoff, preserved voltage “channels” were often identified in the maps with the basket catheter. Therefore, the maps with the mini-basket catheter can rapidly and accurately characterize the complex LV scar, with less extrapolation between points because of the ultra–high-density mapping.

One of the limitations of VT mapping is that most VTs are poorly tolerated hemodynamically. Substrate modification techniques have been developed; however, the long-term success rates are lower with pure substrate ablation than with entrainment mapping techniques. The ability to rapidly map sustained VT, with $<5$ minutes, may represent a real advantage of this approach.

We also showed feasibility for mapping the RV and LV epicardium with a single basket catheter. Such an approach could easily be used in the RV outflow tract or LV epicardium. In some areas of the RV free wall, it was
difficult to obtain good endocardial contact with the basket catheter because of the sharp angulation of the tricuspid valve in the RV of swine. This may or may not be relevant in humans.

The areas demonstrating ILPs have been shown to correlate with areas containing critical isthmuses of the circuits for reentrant tachycardias.\textsuperscript{17} ILPs are located in the scar area, and some may be missed during conventional point-by-point mapping. In this present study, the mini-basket catheter picked up a larger number of ILPs than did the linear catheter. This is likely related to the higher density of mapped points and the smaller electrode size of the basket catheter.

**Study limitations**

To compare the utility of the basket catheter with that of the linear catheter, both catheters used the novel mapping system that allows automatic continuous point acquisition. A comparison between the basket catheter and a commercially available mapping system would have been interesting but would have also been more technically challenging and not a true assessment of the utility of the basket catheter. We were able to show that even the automatic mapping software enhancements, mapping with the basket catheter had advantages compared to mapping with the standard linear catheter.

In our study, mapping of the normal LV was not performed owing to cost limitations. The analysis of an abnormal voltage cutoff value was defined with the electrograms of the healthy area in the infarcted pigs. This may affect the determined cutoff if more diffuse fibrosis was present. However, we believe that this is unlikely, given the localized nature of myocardial infarcts.

As with other available electroanatomic mapping systems, this system cannot automatically distinguish between real low-voltage electrograms and poor contact points. The electrograms of low-voltage areas need to be examined carefully to assure adequate contact. The number of points acquired with the basket catheter allows realistic depiction of cardiac anatomy. However, some valid points, such as those representing papillary muscles, may be automatically rejected by the system if the points are internal and overlapping other external structures.

The time to acquire the maps in use was typically shorter with the basket catheter; however, those data were not included since the maps were often acquired by fellows in various stages of training without a time constraint.

We could not perform entrainment mapping or ablation because of time limitation and animal’s hemodynamic deterioration. However, because we could map 95% of the VT circuit, the mapped reentrant pathway should be useful for guiding ablation of VT.

**Conclusion**

This novel electroanatomic mapping system and a 64-electrode mini-basket catheter allows rapid and detailed voltage and activation mapping in postinfarction cardiomyopathy. This system may be useful for ultra-high-density mapping of the LV endocardium and epicardium in patients with VT.

**References**


Current electroanatomic mapping systems acquire points from a single bipolar or, in some cases, multiple bipoles on a single catheter. We tested a system that allows acquisition of multiple simultaneous electrograms using a 64-electrode mini-basket catheter in a swine model of chronic myocardial infarction and induced ventricular tachycardia (VT). We found that the basket catheter allowed rapid acquisition of ultra-high-density voltage maps. The bipolar voltage cutoffs useful for delineating scar were similar to those used for standard linear catheters. Scar area determined using delayed enhancement magnetic resonance imaging correlated more closely with the basket catheter than with the standard linear catheter. The basket catheter also detected more late potentials, allowed rapid construction of epicardial maps, and allowed rapid acquisition of activation maps during poorly tolerated VT. This system holds promise for decreasing procedure time during VT mapping/ablation procedures by allowing rapid and detailed voltage map acquisition. A detailed depiction of channels within scar and rapid mapping of poorly tolerated VT circuits may also improve the outcome of VT procedures. The next step would be the use of the system in human VT ablation procedures, followed by a randomized comparison of this system with a traditional electroanatomic mapping system during mapping and ablation of human VT.