Atrial fibrillation (AF) ablation is an acceptable therapeutic option for patients with symptomatic AF refractory to medications.1 Pulmonary vein isolation is the cornerstone of the procedure and is associated with a reasonable clinical outcome in patients with paroxysmal AF. However, in patients with persistent AF, pulmonary vein isolation is less effective and additional substrate ablation is frequently performed.2,3 The mechanism of these arrhythmias is usually re-entry involving pre-existing or iatrogenic ablation–related scar tissue.7,8 These circuits are typically challenging to map because of significant scar coupled with fractionated and multicomponent electrograms, limiting local time annotation. In addition, entrainment and postspacing interval mapping techniques may be difficult to perform and interpret because of high output pacing and lack of capture in these areas of low voltage.

The standard catheter for mapping these arrhythmias is a linear catheter with a 3.5-mm distal electrode separated by 2 mm from a proximal 2-mm electrode, resulting in a center-to-center interelectrode spacing of 4.75 mm. As such, each bipolar electrogram represents an underlying tissue diameter ranging from 3.5 to 7.5 mm, depending on the angle of incidence (from perpendicular to parallel to the tissue, respectively). Catheters with 1-mm electrodes, 2-mm interelectrode spacing, and 3-mm center-to-center interelectrode spacing record electrograms from a significantly smaller underlying tissue diameter, ranging from 1 to 4.0 mm (also dependent on catheter orientation relative to the surface). These catheters may have advantages for mapping scar-related arrhythmias, including (1) higher mapping resolution that can identify heterogeneity within the area of low voltage, localizing channels of surviving bundles; (2) smaller electrodes with closer interelectrode spacing are subjected to less signal averaging and cancellation effects, and may thus record higher bipolar voltage amplitude with shorter electrogram duration, allowing more accurate time annotation; (3) pacing with capture at lower output because of increased electric density.

The aims of this study were to (1) establish normal voltage amplitude cutoffs in the atria for both 3.5-mm electrode tip catheters and 1-mm multielectrode-mapping catheters (Pentaray) and to compare their mapping resolution in scar-related atrial arrhythmias. 

Background—The resolution of mapping is influenced by electrode size and interelectrode spacing. Smaller electrodes with closer interelectrode spacing may improve mapping resolution, particularly in scar. The aims of this study were to establish normal electrogram criteria in the atria for both 3.5-mm electrode tip linear catheters (Thermocool) and 1-mm multielectrode-mapping catheters (Pentaray) and to compare their mapping resolution in scar-related atrial arrhythmias.

Methods and Results—Normal voltage amplitude cutoffs for both catheters were validated in 10 patients with structurally normal atria. In 20 additional patients with scar-related atrial arrhythmias, similar sequential mapping with both catheters was performed. Normal bipolar voltage amplitude was similar between 3.5- and 1-mm electrode catheters with a fifth percentile of 0.48 and 0.52 mV, respectively ($P=0.65$). In patients with scar-related atrial arrhythmias, the total area of bipolar voltage <0.5 mV measured using 1-mm electrode catheters was smaller than that measured using 3.5-mm catheter (14.7 versus 20.4 cm$^2$; $P=0.02$). The mean bipolar voltage amplitude in this area of low voltage was significantly higher with 1-mm electrode catheters (0.28 and 0.17 mV; $P=0.01$). Importantly, 54.4% of all low voltage data points recorded with 1-mm electrode catheter had distinct electrograms that allowed annotation of local activation time compared with only 21.4% with 3.5-mm electrode tip catheters ($P=0.01$). Overdrive pacing with capture of the tachycardia from within the area of low voltage was more frequent with 1-mm electrode catheters (66.7 versus 33.4; $P=0.01$).

Conclusions—Mapping with small closely spaced electrode catheters can improve mapping resolution within areas of low voltage. (Circ Arrhythm Electrophysiol. 2015;8:537-545. DOI: 10.1161/CIRCEP.114.002737.)

Key Words: arrhythmias, cardiac □ catheter ablation □ electrophysiology
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 atrial tissue when using 1-mm electrode catheters.
- When compared with standard 4-mm electrode catheters, 1-mm electrode catheters provide higher mapping resolution, especially in areas of low voltage and scar.
- Electrogams recorded with small and closely spaced electrodes have distinct rather than wide fractionated electrograms, allowing more precise determination of local activation time in scar tissue.

(2) compare their mapping resolution in scar-related organized AT.

Methods

Patients

This study included 30 patients. To define normal bipolar electrograms in the atria (voltage amplitude and electrogram duration), we studied 10 patients with paroxysmal AF undergoing index pulmonary vein isolation. In attempt to include only patients with structurally normal atria, eligible patients aged ≥65 years, had paroxysmal AF with arrhythmia duration ≤3 years, lack of valvular disease, and all underwent cardiac magnetic resonance imaging that demonstrated nonscarred atria as evidenced by absence of late gadolinium enhancement. To compare mapping resolution in scar, 20 additional patients with history of prior catheter and surgical ablation and recurrent persistent atrial arrhythmias were also studied. Patients were enrolled prospectively, however, data were analyzed retrospective at the end of the study. The institutional review board of Beth Israel Deaconess Medical Center approved the study protocol and patients provided written informed consent before the clinical procedure.

Mapping Protocol

All procedures were performed under general anesthesia with the use of jet ventilation. Electroanatomic mapping was performed with Carto 3 mapping system (Carto 3 system, Biosense Webster). The linear mapping catheter was an open irrigated mapping/ablation catheter (Thermocool, Biosense Webster, Diamond Bar, CA—linear) and the multielectrode mapping catheter was a 20-pole steerable mapping catheter (Thermocool, Biosense Webster, Diamond Bar, interelectrode spacing 2-6-2 mm—multielectrode-mapping). The linear catheter has a 3.5-mm distal electrode separated by 2 mm from a 2-mm proximal electrode, resulting in 4.75-mm center-to-center spacing. The multielectrode-mapping catheter has 1-mm electrodes with interelectrode spacing of either 2 or 6 mm. For the purpose of this study, we recorded bipolar pairs with interelectrode spacing of 2 mm resulting in 3-mm center-to-center interelectrode spacing. To examine the effect of interelectrode spacing on mapping resolution in scar, a subset of 10 patients with atrial scar underwent similar mapping with both the linear and the multielectrode-mapping catheters. However, in addition, during mapping with the multielectrode-mapping catheter, electrogram were recorded using both bipolar pairs separated by 2 and 6 mm. All bipolar electrograms were filtered between 30 and 500 Hz. Long sheaths were used to support both mapping catheters in the right and left atrium.

Mapping of the Substrate

Mapping of the chamber (right and left atrium) was performed in sinus rhythm. Initial mapping was performed with the linear mapping catheter in point-by-point fashion. In all 10 patients with structurally normal atria in whom normal values were established, the linear mapping catheter was Thermocool Smart Touch that allows force sensing and confirmation of tissue contact. Electrograms were accepted only within a contact force range between 5 and 25 g. Thermocool Smart Touch was also used in 11 of 20 patients with scar-related ATs, using similar criteria. The remaining 9 patients were mapped before contact force catheters were approved for commercial use in the United States, and therefore an ablation catheter without contact force sensing was used. To ensure detailed and uniform mapping of the entire chamber, we set the mapping filling threshold ≤10 mm (allowing interpolation between points to be ≤10 mm) as a requirement for a complete map. In addition, each map made with either the linear or the multielectrode-mapping catheter was registered with cardiac magnetic resonance imaging whenever imaging was available. After completion of the electroanatomical map with the linear catheter, a new shell of the chamber was created with the multielectrode-mapping catheter using similar mapping filling threshold of ≤10 mm. 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 cathery structures. In the group of patients with scar-related ATs, similar sequential mapping with both catheters was performed in sinus rhythm to characterize the substrate and particularly the zone of low voltage and scar. Mapping of 1 or both atria was performed based on the electrocardiographic characteristics of the AT.

Comparison of Pacing Output Threshold

Overdrive pacing of an arrhythmia is often performed in attempt to determine its mechanism and localize its origin. However, pacing with capture is not always possible, particularly in areas of low voltage and scar. In addition, pacing at high output can result in significant artifact precluding its interpretation. Because catheters with smaller electrodes and closer interelectrode spacing have higher current density, we hypothesized they will have lower pacing threshold. We compared pacing output threshold between the linear and the multielectrode-mapping catheters during tachycardia. Pacing with the multielectrode-mapping catheter was performed after completion of the activation map and at multiple atrial sites. Each pacing site was tagged on the electroanatomical shell and pacing output threshold was recorded. Pacing was then repeated with the linear catheter at similar anatomic sites and cycle length. Pacing sites were considered similar if they were within 5 mm from one another. Titration of
pacing output was performed by changing the pacing output strength within a range from 2.0 to 20 mA at constant pulse duration of 2.0 ms. Failure to capture was defined as lack of capture at 20 mA at 2 ms.

Radiofrequency Ablation
Ablation of ATs was guided by activation and entrainment mapping. In re-entrant circuits, radiofrequency ablation was performed in attempt to disrupt the circuit with a line applied between 2 anatomic barriers (ie, mitral annulus to left inferior pulmonary vein in mitral annular flutter) or at the earliest activation site of focal non-re-entrant tachycardias. Ablation was performed using the 3.5-mm open irrigated catheter with energy of 20 to 40 W. Energy was titrated to achieve a 10 to 15 Ohms impedance decrease. If the AT terminated during radiofrequency ablation, rapid atrial pacing was performed in attempt to reinduce the arrhythmia. If it remained noninducible, the ablation was considered successful. When linear ablation was used across an isthmus, activation mapping or differential pacing on either side of the ablation line was performed to confirm bidirectional block.

Electrogram Measurement Protocol
To define the lower normal voltage cutoffs in the healthy right and left atria, we analyzed data from 10 control patients with structurally normal atria and determined the fifth percentile of the bipolar voltages amplitude. To measure bipolar signal duration in normal atria with both catheters, data were analyzed off-line with electronic calipers on the Prucka CardioLab (GE Healthcare, Waukesha, WI) recording system using uniform lead gain and article speed of 200 mm/s. The local atrial 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 presence of fractionation (defined as signals with multiple intrinsic deflections), split potentials (defined as electrograms separated by ≥50 ms by an isoelectric interval), and late potentials (defined as those displaying an additional signal separated from the local atrial electrogram by ≥50 ms).

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. A P value <0.05 was considered statistically significant. Analyses were conducted using SPSS Statistics 20.0 (Chicago, IL).

Results
Patient Characteristics and Previous Ablations
Patient characteristics are depicted in Table 1. In the derivation group of 10 patients with structurally normal atria, the mean age was 55±9 years and the mean left atrial diameter was 40±6 mm. The mean ejection fraction was 60±10%. All patients had cardiac magnetic resonance imaging without evidence of late gadolinium enhancement (indicative of scar) in the atria.2 In the group of patients with scar-related ATs, 16 had prior percutaneous ablation procedures (median of 2 prior procedures per patient) and 4 additional patients had history of surgical maze. Six patients had previously undergone mitral valve replacement surgery. The recurrent arrhythmia was persistent ATs in 14 patients and persistent AF in 6 patients. The mean time from the prior ablation or surgical procedure to the current ablation procedure was 13.3±9.2 months (range, 3–23 months).

Mapping Density
In the derivation group of 10 patients with structurally normal atria, the number of electrograms acquired with the multielectrode-mapping catheter was significantly greater than that obtained with the linear catheter (right atrium 1286±336 [median, 1220] versus 462±216 [median, 446], P<0.01; left atrium 1554±374 [median, 1335] versus 366±273 [median, 352], P<0.01). The mapping time was shorter using the multielectrode-mapping catheter (13±7 minute [median, 12] versus 21±12 minutes [median, 20], P=0.03). This is likely because each beat acquired with the multielectrode-mapping catheter can record ≤10 overlapping bipolar electrograms compared with only 1 bipolar electrogram recorded with a linear catheter. Similarly, in the group of patients with scar-related atrial arrhythmias, mapping density was higher with the multielectrode-mapping catheter (1858±975 [median, 1766] versus 472±171 [median, 452]; P<0.01) despite shorter mapping times (15±6 minutes [median, 15] versus 23±12 minutes [median, 22], P=0.02).

Normal Cutoff Values
Normal voltage cutoffs for each catheter were established in 10 patients with structurally normal atria during sinus rhythm. In the right atrium, a total of 4382 electrograms were recorded with the linear catheter and a total of 11 956 with the multielectrode-mapping catheter. The mean bipolar electrogram amplitude was similar between the linear and the multielectrode-mapping catheters (2.6±1.8 versus 2.9±2.4 mV; P=0.76). The fifth percentile of the normal bipolar voltage distribution was also similar between the linear and multielectrode-mapping catheters (0.48 and 0.52 mV, respectively; P=0.68). In the left atrium, a total of 3852 electrograms were recorded with the linear catheter and a total of 16 435 with the multielectrode-mapping catheter. The mean bipolar electrogram amplitude recorded was similar between

<table>
<thead>
<tr>
<th>Variable</th>
<th>Validation Group (n=10)</th>
<th>Scar-Related Atrial Arrhythmias (n=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>55.2±9.3</td>
<td>64.2±11.3</td>
</tr>
<tr>
<td>Sex, men</td>
<td>7 (70)</td>
<td>14 (70)</td>
</tr>
<tr>
<td>LA diameter, mm</td>
<td>40.4±6.1</td>
<td>56.7±11.5</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>60.3±9.7</td>
<td>48.4±8.4</td>
</tr>
<tr>
<td>No. of failed AADs</td>
<td>1 (0–2)</td>
<td>2 (1–3)</td>
</tr>
<tr>
<td>Mitral regurgitation</td>
<td>27 (67.5)</td>
<td>45 (70.3)</td>
</tr>
<tr>
<td>≥Mild degree</td>
<td>0 (0)</td>
<td>11 (55)</td>
</tr>
<tr>
<td>Failed previous ablations</td>
<td>0 (0)</td>
<td>2 (0–4)</td>
</tr>
<tr>
<td>Surgical maze</td>
<td>0 (0)</td>
<td>4 (20)</td>
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<tr>
<td>Surgical MV replacement</td>
<td>0 (0)</td>
<td>6 (30)</td>
</tr>
<tr>
<td>Presenting arrhythmia</td>
<td>Paroxysmal AF</td>
<td>10 (100)</td>
</tr>
<tr>
<td></td>
<td>Persistent AF</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>AT</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

Values are expressed as mean±SD, median (range), or n (%). AADs indicates antiarrhythmic drugs; AF, atrial fibrillation; AT, atrial tachycardia; LA, left atrium; LVEF, left ventricular ejection fraction; and MV, mitral valve.
the linear and the multielectrode-mapping catheters (2.6±1.6 versus 2.8±3.2 mV; P=0.84). The fifth percentile of normal bipolar voltage distribution was also similar between the linear and multielectrode-mapping catheters (0.50 and 0.52 mV, respectively; P=0.80). Using this data, we defined the normal atrial endocardial bipolar voltage amplitude as ≥0.5 mV and similar between both catheters.

Electrogram duration during sinus rhythm was shorter with the multielectrode-mapping catheter. When mapping with the multielectrode-mapping catheter, the mean bipolar electrogram duration was 32±22 ms (median, 30ms; range, 18–54 ms) and 95% of all electrograms had duration <46 ms. In comparison, when mapping the linear catheter, the mean bipolar electrogram duration was 44±24 ms (median, 42 ms; range, 26–68 ms) and 95% of all electrograms had a duration <58 ms.

Low Voltage (Scar) Mapping

We compared mapping resolution between the 2 catheters in low voltage and scar tissue during sinus rhythm. In patients with scar-related atrial arrhythmias, the total area of low bipolar voltage (defined as <0.5 mV) measured using the multielectrode-mapping catheter was significantly smaller than that measured using the linear catheter (14.7 cm² [median, 15.2; range, 7–48 cm²] versus 20.4 cm² [median, 22.4; range, 9–55 cm²]; P=0.02). In addition to smaller low voltage scar area, the bipolar voltage distribution within this area of low voltage was higher using multielectrode-mapping catheters with a mean bipolar voltage of 0.28±1.2 mV compared with 0.17±1.0 mV measured with the linear catheter (P<0.01). This resulted in improved delineation of the low voltage zones (Table 2; Figures 1 and 2).

Late potentials within the area of low voltage (<0.5 mV) were more frequently recorded with the multielectrode-mapping catheter (28.2±14.5% versus 13.6±7.8% of total low voltage signals; P=0.01). Electrogram fractionation within the area of low voltage was also more frequently recorded with multielectrode-mapping catheters (68.8±22.6% versus 38.6±12.4% of total low voltage signals; P<0.01). These signals were essentially seen only in the group of patients with scarred atria. The frequency of split potentials was similar between the catheters.

Determinants of Mapping Resolution Within Scar

We examined the individual contribution of (1) mapping density, (2) electrode size, and (3) interelectrode spacing on catheter mapping resolution within the zone of low voltage.

To examine the relationship between mapping density and mapping resolution, each pair of maps was reanalyzed and density adjusted by excluding data points from the map of greater original density to achieve similar data density with homogenous point distribution. To minimize bias, all data points were exported to a Matlab platform and distances between points were calculated based on the x, y, and z coordinates. Exclusion of points was performed blindly based on data point coordinates and aimed to create a similar point data density between maps. The resultant mean mapping density was 12±3 mm between points with a lowest density of 15 mm (allowing interpolation between points to be ≤15 mm). The total area of bipolar voltage <0.5 mV measured with the multielectrode-mapping catheter remained significantly smaller than that measured with linear catheter (15.4 cm² [median, 12.8; range, 7–32.6 cm²] versus 22.4 cm² [median, 21.8; range, 11–44 cm²]; P=0.03). The mean bipolar voltage amplitude within this area of low voltage remained higher when using the multielectrode-mapping catheter (0.26±0.12 versus 0.17±0.09 mV; P=0.01). This data suggest that mapping density is not a significant determinant in the differential resolution between the catheters.

To examine the relationship between electrode size and bipolar voltage amplitude, we first attempted to control for the other 2 variables, mapping density and interelectrode spacing. Mapping density was controlled as described above with all paired maps having similar mapping density. As the catheters do not have similar interelectrode spacing, we reanalyzed maps made with the multielectrode-mapping catheter to only include data from bipolar electrode pairs separated by 6 mm rather than 2 mm. In this configuration, the relationship of interelectrode spacing between the catheters had reversed with the multielectrode-mapping catheter having a larger center-to-center interelectrode spacing compared with the linear catheter (7 versus 4.75 mm). The total area of bipolar voltage <0.5 mV measured with the multielectrode-mapping catheter remained smaller than that measured with the linear catheter (18.6 cm² [median, 15.2; range, 9–24.8 cm²] versus 22.4 cm² [median, 23.1; range, 11–36.6 cm²]; P=0.04). The mean bipolar voltage amplitude recorded with the multielectrode-mapping catheter remained higher (0.22±0.10 versus 0.17±0.09 mV; P=0.04). This data suggest that smaller size electrodes are at least partially responsible for the differential resolution between the catheters.

Lastly, we examined the relationship between interelectrode spacing and bipolar voltage amplitude. A subset of 10 patients with scar-related atrial arrhythmias underwent mapping with the multielectrode-mapping catheter recording both bipolar electrode pairs separated by 2 and 6 mm. This data were then separated into 2 data sets, 1 containing only data recorded using bipolar electrodes separated by 2 mm and a second

Table 2. Comparison of Low Voltage and Scar Surface Area

<table>
<thead>
<tr>
<th></th>
<th>Linear Catheter</th>
<th>Multielectrode-Mapping Catheter</th>
<th>P Value (Linear vs Multielectrode-Mapping Catheter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total low voltage area</td>
<td>20.4 cm²</td>
<td>14.7 cm²</td>
<td>0.02</td>
</tr>
<tr>
<td>(Median, 25%, 75%)</td>
<td>9–55 cm²</td>
<td>7–48 cm²</td>
<td></td>
</tr>
<tr>
<td>Intermediate area</td>
<td>22.4, 18.1, 50.6</td>
<td>15.2, 9.2, 43.6</td>
<td>0.02</td>
</tr>
<tr>
<td>0.25–0.5 mV, cm²</td>
<td>5.2, 3.8, 9.9</td>
<td>8.8, 4.7, 11.6</td>
<td></td>
</tr>
<tr>
<td>(Median, 25%, 75%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dense scar</td>
<td>14.2±8.1</td>
<td>4.3±3.6</td>
<td>0.01</td>
</tr>
<tr>
<td>(&lt;0.25 mV, cm²)</td>
<td>16.6, 10.2, 18.5</td>
<td>4.0, 2.1, 6.8</td>
<td></td>
</tr>
<tr>
<td>(Median, 25%, 75%)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are expressed as mean±SD, range [ ].
containing only data recorded using bipolar electrode separated by 6 mm. The total low voltage area and mean bipolar voltage amplitude was calculated for each separate map. The total area of bipolar voltage <0.5 mV measured with interelectrode spacing of 2 mm was smaller than that measured with interelectrode spacing of 6 mm catheter (15.4 cm² [median, 14.0; range, 8–23.5 cm²] versus 19.2 cm² [median, 18.6; range, 10–28.9 cm²]; \( P = 0.03 \)). The mean bipolar voltage amplitude within this area of low voltage was higher when mapping with interelectrode spacing of 2 mm (0.26±0.11 versus 0.22±0.16 mV).

Figure 1. Left atrial bipolar voltage maps (0.10–0.50 mV) in the posterior–anterior view recorded with a standard linear catheter (A) and a multielectrode catheter (B) in a patient with structurally normal left atria. The left atrial bipolar voltage amplitude was similar between the maps with 95% of all electrograms >0.5 mV. In contrast, in a patient with scar-related atrial tachycardia, the bipolar voltage amplitude measured with the linear catheter (C) was significantly lower than the one measured with the multielectrode catheter (D).

Figure 2. Left atrial bipolar voltage maps (0.10–0.50 mV) in the anterior–posterior view recorded with a multielectrode catheter (A) and a linear catheter (B) in a patient with scar-related atrial tachycardia. Mapping with the multielectrode catheter demonstrated a significantly smaller area of low voltage and scar in the anterior perimitral area. The 2 catheters were then placed in contact with the zone of presumed scar as recorded with the linear catheter but not with the multielectrode catheter (C). The mean bipolar voltage amplitude recorded with the multielectrode catheter at this location was 1.15±0.7 mV with mean electrogram duration of 42±11 ms and minimal fractionation (D), suggestive of nonscar tissue.
mV; \( P=0.03 \)). This data suggest that interelectrode spacing is a determinant of mapping resolution within scar tissue.

**Arrhythmia Mapping**

Twenty patients with scar-related atrial arrhythmias had 26 ATs; however, only 23 had TCL \( \geq 200 \text{ ms} \) (mean, 274±56 ms) that allowed mapping. Five ATs were not mapped because they stopped spontaneously before mapping and did not recur. Activation mapping was performed with the multielectrode-mapping catheter in all 18 sustained ATs and with the linear catheter in 13 of the 18 (72.2%). In effort to limit bias, the sequence of mapping alternated between the catheters, with the linear catheter used first in 8 patients and the multielectrode-mapping catheter used first in 5 patients. The mechanism of the tachycardia was defined as macro–re-entry or focal micro–re-entry on the basis of the activation map. In macro–re-entrant atrial tachycardias, the circuits traversed large portions of the atrium, whereas in focal atrial tachycardias, a point source with centrifugal activation from this center was identified. The mechanism was macro–re-entry in 16 of 18 (88.9%) and focal in 2 of 18 (11.1%). The most common atrial tachycardia was a macro–re-entrant circuit involving the mitral isthmus (8 of 16; 50%) followed by macro–re-entrant circuit involving the left atrial roof (4 of 16; 25%). The third most common tachycardia (3 of 18; 17%) involved the septum, and there was 1 right-sided atrial tachycardia.

Activation mapping with the multielectrode-mapping catheter included a mean of 1172±346 points (median, 1220) with an average mapping time of 13±8 minutes (median, 14). The activation map constituted an average of 92±8% of the TCL. All circuits involved the area of low voltage as defined with the multielectrode-mapping catheter during sinus rhythm. In 12 of the 16 macro–re-entrant ATs mapped with the multielectrode-mapping catheter, activation mapping was also performed using the linear catheter. The mean number of activation points per map was smaller (241±73; median, 228; \( P=0.02 \)) despite similar mapping time of 15±11 minutes (median, 15; \( P=0.72 \)). In comparison with mapping with the multielectrode-mapping catheter, activation maps constituted an average of 68±32% of the TCL (\( P=0.01 \)). In 4 ATs that occurred in patients with limited atrial scar, mapping with either the linear or the multielectrode-mapping catheter resulted in nearly complete activation map constituting >90% of the TCL. However, in 8 ATs that occurred in patients with extensive atrial scarring, mapping with the linear catheter was associated with limited activation mapping constituting only 53±11% of the TCL compared with 90±8% when the same AT was mapped with the multielectrode-mapping catheter (Figures 3 and 4). In these cases, mapping with the linear catheter demonstrated significantly lower mean voltage amplitude that was coupled with highly fractionated and nondistinctive electrograms, limiting accurate activation mapping.

**Figure 3.** In a patient with history of surgical maze, mitral valve replacement, and persistent atrial tachycardia, left atrial bipolar voltage maps were performed using both a multielectrode catheter (A) and a standard linear catheter (B). Mapping with the multielectrode catheter demonstrated smaller scar size with an overall higher bipolar voltage amplitude. When the bipolar voltage maps were displayed at a range of 0.1 to 0.25 mV, the map made with the multielectrode catheter demonstrated improved delineation of the low voltage zone, revealing an area of relatively preserved myocardium (channel) that was not demonstrated in a map made with the linear catheter (C and D). When the clinical atrial flutter was mapped, this channel proved to be the isthmus of the tachycardia as seen by the activation map (E). When the multielectrode catheter was placed over the isthmus, >75% of the tachycardia cycle length was recorded at this single-point acquisition (F). The tachycardia terminated with ablation at this site.
time annotation (Figure 5). Overall, 54.4% of all low voltage data points recorded with multielectrode-mapping catheters had distinct electrograms that allowed annotation of local activation time compared with only 21.4% of all low voltage points recorded with linear catheters ($P=0.02$). Ablation was successful in 15 of the 16 macro–re-entrant circuits and in the 2 focal arrhythmias. In 1 patient with macro–re-entrant circuit involving the interatrial septum ablation was unsuccessful.

Atrial Pacing Threshold

We compared the pacing threshold during tachycardia between the linear and multielectrode-mapping catheters at similar atrial sites. In 13 patients in whom the arrhythmia was mapped with both catheters, overdrive pacing of the tachycardia was performed with both the linear and the multielectrode-mapping catheters ($n=54$ and $47$, respectively). Pacing with capture was more frequent with multielectrode catheters (66.7% versus 33.4%; $P=0.01$). Moreover, the pacing threshold was

Figure 4. In a patient with macro–re-entrant left atrial flutter, the multielectrode catheter and the linear catheter were placed at a similar position at the area of early meet late. The linear catheter was positioned in a perpendicular orientation to the tissue with its distal electrode applying 9 g of tissue contact force. The multielectrode catheter was positioned parallel to the tissue (A). Although the linear catheter recorded low, far-field, signal with amplitude of 0.12 mV, the multielectrode catheter recorded sharp, near-field, signals with bipolar amplitude range of 0.18–0.28 mV that allowed both local time annotation and pacing with capture (B).

Figure 5. In a patient with history of surgical maze, 2 previous percutaneous left atrial ablation procedures and mitral valve replacement, a left atrial flutter was mapped with both the standard linear and the multielectrode catheter. A bipolar voltage map made with the linear catheter demonstrated diffuse and homogenous scar with bipolar voltage amplitude <0.5 mV, limiting activation and entrainment mapping (A). When the multielectrode catheter was placed at the perimitral area alongside the linear ablation catheter, fractionated mid diastolic electrograms with bipolar voltage amplitude range of 0.18–0.34 mV were recorded (A). B, Overdrive pacing with capture from a single electrode of the multielectrode catheter entrained the tachycardia in orthodromic fashion and a post pacing interval that was 13 ms longer than the tachycardia cycle length. A linear ablation between the mitral valve and the left inferior pulmonary vein terminated the tachycardia.
lower using multielectrode-mapping catheters as 57.7% of pacing sites had threshold ≤10 mA at 2 ms compared with only 25.5% when pacing from a linear catheter (P=0.02).

Discussion

Major Findings

This study established the normal bipolar voltage distributions in the atria for both a linear catheter with 3.5-mm distal electrode and 1-mm multielectrode-mapping catheter. In addition, this study compared the mapping resolution in low voltage and scar with both catheters.

The major findings are (1) bipolar voltage amplitude in healthy atria is similar between 3.5- and 1-mm electrode catheters with a fifth percentile of 0.48 and 0.52 mV, respectively; (2) mapping resolution within areas of low voltage and scar is enhanced with 1-mm electrode catheters; (3) electrode size and interelectrode spacing were major determinants of mapping resolution within areas of low voltage and scar; (4) lastly, arrhythmia mapping using activation and overdrive pacing techniques was more accurate using 1-mm electrode catheters.

Three-dimensional electroanatomic mapping systems have been developed to assist with mapping and ablation of cardiac arrhythmias. These systems have become an essential tool for mapping complex arrhythmias and are frequently used to assess the underlying substrate for presence of low voltage areas, so-called scar. Accurate detection and characterization of atrial scar with electroanatomic mapping is essential for catheter ablation of atrial arrhythmias. Normal electrographic criteria in the ventricle were defined by Cassidy et al9 and Marchlinski et al,10 however, limited data exist about the normal voltage distribution in the atria. Kapa et al have defined the normal bipolar voltage distribution in the left atrium using 3.5-mm Thermocool catheter. In 10 patients with paroxysmal AF, the mean bipolar voltage amplitude was 1.44±1.27 mV, and 95% of all points demonstrated a bipolar voltage amplitude >0.45 mV. Our study confirms this observation and extends its finding also to the right atrium. We found that 95% of all electrograms in the right and left atria had a bipolar voltage amplitude >0.48 mV. In addition, we measured the distribution of electrograms duration in healthy atria and found that 95% of all electrograms had a duration <58 ms.

Iatrogenic AT are unfortunately common after AF ablation, particularly in patients with persistent AF where additional ablation sets often include linear lesions and ablation at sites of complex fractionated electrograms. The mechanism of these ATs is typically macro-re-entry but also sometimes micro-re-entry involving pre-existing or iatrogenic ablation-related scar tissue. These arrhythmias can be challenging to map using standard linear catheters because of significant scar coupled with fractionated and multicomponent electrograms, limiting activation, and entrainment mapping. Patel et al11 have reported the feasibility to rapidly map and successfully ablate these arrhythmias using the Pentaray multielectrode-mapping catheter in post–pulmonary vein isolation patients with ATs.

In this study, we established the normal atrial electrogram characteristics of 2 commonly used catheters: a standard mapping/ablation catheter (Thermocool) and a multielectrode-mapping catheter (Pentaray). Although the resolution of mapping between the catheters was similar in healthy atrial tissue, they significantly diverge in low voltage and scar tissue. The resolution of electric mapping is influenced by multiple parameters, 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. While these changes may not be as clinically important in the normal healthy tissue, whereas a bipolar voltage amplitude variation between 0.5 and 4.0 mV represents normal tissue, such variations in areas of low voltage and scar are significant and determine feasibility to identify surviving myocardial channels and isthmuses often present in zones of low voltage. In this study, we found that smaller electrodes with closer interelectrode spacing provide higher resolution in scar mapping. Maps made with multielectrode-mapping catheters usually contained more data points, and points acquired with increased variability in the angle of incidence and the relationship to the vector of propagation. They may thus be less subjective to the individual confounding effects of bipolar voltage amplitude measurement. We found that mapping density alone is not responsible for the differences in mapping resolution within scar and that smaller electrodes and closer interelectrode spacing are significant determinants of mapping resolution. Smaller electrodes have smaller electrical fields of view and smaller antenna, and as such are subjected to less averaging and cancellation effects. A bipolar electrode pair with closer interelectrode spacing record data from smaller tissue diameters and is therefore more sensitive to detect surviving myocardial fibers in zones of generally low voltage channels. It also has a more distinct electrogram with shorter electrogram duration that allows more accurate annotation of activation time. Lastly, the pacing output threshold within the zone of low voltage and scar is lower with small electrode catheters, likely because of the increased electric current density at the electrode-tissue interface.

In addition, pacing from a multielectrode-mapping catheter placed in or around a macro-re-entrant circuit can be used to determine the mechanism of the tachycardia. If pacing performed during AT from a site that demonstrates later activation relative to its neighbors results in orthodromic capture of these earlier upstream neighboring sites, the mechanism must be re-entry. Barbhaiya et al12 have recently reported the use of such approach to define the mechanism of atrial tachycardias.

Limitations

This study includes a relatively small cohort of patients. Although mapping data with the linear catheter was confirmed by contact force measurement, such data were not available for maps made with the multielectrode-mapping catheter. However, although differences in tissue contact can affect bipolar voltage amplitude, it is unlikely to account for the differences between the catheters. First, all maps performed with multielectrode-mapping catheters had similar volumes compared with maps made with linear catheters. Second, points were only accepted if they were within 5 mm from the original shell made with the linear catheter. Lastly, in the derivation cohort of patients with normal atria, the bipolar voltage...
amplitude was similar between the catheters. In patients with ATs, only 13 of the 18 ATs mapped with the multielectrode-mapping catheter were also mapped with the linear catheter. Although the number of ATs mapped with both catheters was small, the data were highly consistent. Electrogram duration was measured using fixed electrogram gain; however, data acquisition was obtained using a standard amplifier with variable gain. The clinical impact of mapping with small electrode catheters on long-term clinical outcome is outside the scope of this study and remains unanswered. Finally, it may be economically challenging to use the Pentaray catheter in addition to a circular mapping catheter commonly used during routine AF ablation procedures. However, in our experience, we have been able to perform the entire ablation procedure using just the Pentaray catheter instead of the circular catheter, including creating the left atrial geometry and verifying entrance and exit blocks.

Conclusions
This study established the normal bipolar voltage criteria in the atria for both a standard linear mapping/ablation catheter with 3.5-mm distal electrode (Thermocool) and a multielectrode-mapping catheter with 1-mm electrodes (Pentaray). In addition, this study showed that catheters with smaller electrodes and closer interelectrode spacing have significant advantage in mapping atrial scar. This technique can facilitate successful ablation of scar-related atrial tachycardias.

Disclosures
Dr Anter receives research grants and speaking honoraria from Biosense Webster and Boston Scientific. Dr Josephson receives research grants and speaking honoraria from Medtronic. C. M. Tschabrunn reports no conflicts.

References


High-Resolution Mapping of Scar-Related Atrial Arrhythmias Using Smaller Electrodes With Closer Interelectrode Spacing

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