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

Running title: Anter et al.; High resolution scar mapping

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Abstract:

**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 3.5mm electrode tip linear catheters (Thermocool®) and 1mm 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 3.5mm and 1mm electrode catheters with a 5th percentile of 0.48mV and 0.52mV, respectively (p=0.65). In patients with scar-related atrial arrhythmias, the total area of bipolar voltage <0.5mV measured using 1mm electrode catheters was smaller than that measured using 3.5mm catheter (14.7cm² vs 20.4cm²; p=0.02). The mean bipolar voltage amplitude in this area of low voltage was significantly higher with 1mm electrode catheters (0.28mV and 0.17mV, p=0.01). Importantly, 54.4% of all low voltage data points recorded with 1mm electrode catheter had distinct electrograms that allowed annotation of local activation time compared with only 21.4% with 3.5mm electrode tip catheters (p=0.01).

Overdrive pacing with capture of the tachycardia from within the area of low voltage was more frequent with 1mm electrode catheters (66.7 vs 33.4; p=0.01).

**Conclusions** - Mapping with small closely spaced electrode catheters can improve mapping resolution within areas of low voltage.

**Key words:** ablation, mapping, electrophysiology, arrhythmia
Introduction

Atrial fibrillation (AF) ablation is an acceptable therapeutic option for patients with symptomatic AF refractory to medications. Pulmonary vein isolation (PVI) 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, PVI is less effective and additional substrate ablation is frequently performed. This approach often results in the development of post-ablation, scar-related, organized atrial tachyarrhythmias.

The mechanism of these arrhythmias is usually reentry involving preexisting or iatrogenic ablation-related scar tissue. 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 post-pacing interval mapping techniques may also be difficult to perform and interpret due to high output pacing and/or lack of capture in these areas of low voltage.

The standard catheter for mapping these arrhythmias is a linear catheter with a 3.5mm distal electrode separated by 2mm from a proximal 2mm electrode, resulting in a center-to-center interelectrode spacing of 4.75mm. As such, each bipolar electrogram represents an underlying tissue diameter ranging from 3.5mm to 7.5mm, depending on the angle of incidence (from perpendicular to parallel to the tissue, respectively). Catheters with 1mm electrodes, 2mm interelectrode spacing, and 3mm center-to-center interelectrode spacing record electrograms from a significantly smaller underlying tissue diameter, ranging from 1mm to 4.0mm (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 due to increased electrical density.

The aims of this study were to: 1) establish normal voltage amplitude cutoffs in the atria for both 3.5mm electrode tip catheters and 1mm multielectrode-mapping catheters; 2) compare their mapping resolution in scar-related organized atrial tachyarrhythmias (AT).

Methods

Patients

This study included 30 patients. In order to define normal bipolar electrograms in the atria (voltage amplitude and electrogram duration), we studied 10 patients with paroxysmal AF undergoing index PVI. In attempt to include only patients with structurally normal atria, eligible patients were ≤65 year-old, had paroxysmal AF with arrhythmia duration ≤ 3 years, lack of valvular disease, and all underwent cardiac magnetic resonance imaging (CMR) that demonstrated non-scarred atria as evidenced by absence of late gadolinium enhancement. In order to compare mapping resolution in scar, 20 additional patients with history of prior catheter and / or surgical ablation and recurrent persistent atrial arrhythmias were also studied. Patients were enrolled prospectively, however data was 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 prior to 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 arranged in 5 soft radiating spines covering a diameter of 3.5cm (Pentaray®, Biosense Webster; Diamond Bar; interelectrode spacing 2-6-2mm - “multielectrode-mapping ”). The linear catheter has a 3.5mm distal electrode separated by 2mm from a 2mm proximal electrode, resulting in 4.75mm center-to-center spacing. The multielectrode-mapping catheter has 1mm electrodes with interelectrode spacing of either 2 or 6 mm. For the purpose of this study, we recorded bipolar pairs with interelectrode spacing of 2mm resulting in 3mm center-to-center interelectrode spacing. In order 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 6mm. 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 5-25 grams. Thermocool Smart Touch® was also used in 11 of the 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 US, 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 \( \leq 10\text{mm} \) (allowing interpolation between points to be \( \leq 10\text{mm} \)) as a requirement for a complete map. In addition, each map made with either the linear or the multielectrode-mapping catheters was registered with CMR 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 \( \leq 10\text{mm} \). 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 5mm from the original shell made with contract force technology. This algorithm, although not an equivalent to tissue contact, can potentially reduce mapping of cavitary structures. In the group of patients with scar-related ATs, similar sequential mapping with both catheters was performed in sinus rhythm in order to characterize the substrate and particularly the zone of low voltage and scar. Mapping of one or both atria was performed based on the electrocardiographic characteristics of the AT.

**Mapping of the arrhythmia**

In the group of patients with scar related atrial arrhythmias, 14 patients had 26 ATs while 6 had AF. We attempted to map all ATs with both catheters. Electrograms were selected for local time annotation if their bipolar voltage amplitude was \( >0.06\text{mV} \) (2-fold higher than the noise level in our lab) and had distinct and reproducible near-field potentials. Once activation maps were completed and the putative circuit identified, overdrive pacing was performed in order to entrain the tachycardia and further characterize the circuit. Entrainment pacing was performed at a cycle length 10-25 msec faster than the tachycardia. The pacing site was considered part of the circuit if the post-pacing interval measured from the stimulation artifact to the return atrial electrogram.
on the ablation catheter was within 25 msec of the tachycardia cycle length (TCL). Pacing at multiple sites was performed with both the linear and multielectrode-mapping catheters.

**Comparison of pacing output threshold**

Overdrive pacing of an arrhythmia is often performed in attempt to determine its mechanism and/or 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. As 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 anatomical sites and cycle length. Pacing sites were considered similar if they were within 5mm 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 a constant pulse duration of 2.0 msec. Failure to capture was defined as lack of capture at 20mA at 2ms.

**Radiofrequency ablation**

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

**Electrogram measurement protocol**

In order 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 5\textsuperscript{th} percentile of the bipolar voltages amplitude. In order to measure bipolar signal duration in normal atria with both catheters, data was analyzed offline with electronic calipers on the Prucka CardioLab (GE Healthcare, Waukesha, Wisconsin) recording system using uniform lead gain and paper 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. In order 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 ≥30msec by an isoelectric interval), and late potentials (defined as those displaying an additional signal separated from the local atrial electrogram by ≥ 50msec).

**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 one sample Kolmogorov-Smirnov test and comparisons between the linear and multielectrode-mapping data were performed using the unpaired Student’s t test or Mann-Whitney U test as appropriate. Categorical variables were compared using the Fisher’s
exact test. A p value <0.05 was considered statistically significant. Analyses were conducted using SPSS Statistics 20.0 (Chicago, Illinois).

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±6mm. The mean ejection fraction was 60±10%. All patients had CMR without evidence late gadolinium enhancement (indicative of scar) in the atria. 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 to 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] vs. 462±216 [median 446], p<0.01; left atrium 1554±374 [median 1335] vs. 366±273 [median 352], p<0.01). The mapping time was shorter using the multielectrode-mapping catheter (13±7min [median 12] vs. 21±12mm [median 20], p=0.03). This is likely because each “beat” acquired with the multielectrode-mapping catheter can record up to 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] vs. 472±171 [median 452], p<0.01) despite shorter mapping times 
(15±6min [median 15] vs. 23±12min [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±1.8mV vs. 2.9±2.4mV; p=0.76). The fifth percentile of the normal bipolar voltage distribution was also similar between the linear and multielectrode-mapping catheters (0.48mV and 0.52mV, respectively; p=0.68). In the left atrium, a total of 3852 electrograms were recorded with the linear catheter and a total 16,435 electrograms with the multielectrode-mapping catheter. The mean bipolar electrogram amplitude recorded was similar between the linear and the multielectrode-mapping catheters (2.6±1.6mV vs. 2.8±3.2mV; p=0.84). The fifth percentile of normal bipolar voltage distribution was also similar between the linear and multielectrode-mapping catheters (0.50mV and 0.52mV, respectively; p=0.80). Using this data, we defined the normal atrial endocardial bipolar voltage amplitude as ≥0.5mV 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 32msec +/- 22 (median 30msec; range 18-54ms) and 95% of all electrograms had duration <46ms. In comparison, when mapping the linear catheter, the mean bipolar electrogram duration was 44msec +/-24 (median 42msec; range 26-68ms) and 95% of all electrograms had a duration <58msec.
Low voltage (“scar”) mapping

We compared mapping resolution between the two 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 <0.5mV) measured using the multielectrode-mapping catheter was significantly smaller than that measured using the linear catheter (14.7cm² [median 15.2; range 7-48cm²] vs. 20.4cm² [median 22.4; range 9-55cm²]; 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+/− 1.2mV compared with 0.17+/− 1.0mV measured with the linear catheter (p=0.01). This resulted in improved delineation of the low voltage zones (Table 2 and Figures 1 and 2).

Late potentials within the area of low voltage (<0.5mV) were more frequently recorded with the multielectrode-mapping catheter (28.2+/−14.5% vs. 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% vs. 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.

In order 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 in order to achieve similar data density with homogenous point distribution. In order 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±3mm between points with a lowest density of 15mm (allowing interpolation between points to be ≤15mm). The total area of bipolar voltage <0.5mV measured with the multielectrode-mapping catheter remained significantly smaller than that measured with linear catheter (15.4cm² [median 12.8; range 7-32.6cm²] vs. 22.4cm² [median 21.8; range 11-44cm²]; p=0.03). The mean bipolar voltage amplitude within this area of low voltage remained higher when using the multielectrode-mapping catheter (0.26+/−0.12mV vs. 0.17+/−0.09mV; p=0.01). This data suggests that mapping density is not a significant determinant in the differential resolution between the catheters.

In order to examine the relationship between electrode size and bipolar voltage amplitude, we first attempted to control for the other two 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 6mm rather than 2mm. 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 vs. 4.75mm). The total area of bipolar voltage <0.5mV measured with the multielectrode-mapping catheter remained smaller than that measured with the linear catheter (18.6cm² [median 15.2; range 9-24.8cm²] vs. 22.4cm² [median 23.1; range 11-36.6cm²]; p=0.04). The mean bipolar voltage amplitude recorded with the multielectrode-mapping catheter remained higher (0.22+/−0.10mV vs. 0.17+/−0.09mV; p=0.04). This data suggests 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 6mm. This data was then separated into two datasets, one containing only data recorded using bipolar electrodes separated by 2mm and a second containing only data recorded using bipolar electrode separated by 6mm. The total low voltage area and mean bipolar voltage amplitude was calculated for each separate map. The total area of bipolar voltage <0.5mV measured with interelectrode spacing of 2mm was smaller than that measured with interelectrode spacing of 6mm catheter (15.4cm² [median 14.0; range 8-23.5cm²] vs. 19.2cm² [median 18.6; range 10-28.9cm²]; p=0.03). The mean bipolar voltage amplitude within this area of low voltage was higher when mapping with interelectrode spacing of 2mm (0.26+/-0.11mV vs. 0.22+/-0.16mV; 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 ≥ 200ms (mean 274±56ms) 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 macroreentry or focal microreentry on the basis of the activation map. In macroreentrant atrial tachycardias, the circuits
traversed large portions of the atrium while in focal atrial tachycardias a point source with centrifugal activation from this center was identified. The mechanism was macroreentry in 16 of 18 (88.9%) and focal in 2 of 18 (11.1%). The most common atrial tachycardia was a macroreentrant circuit involving the mitral isthmus (8 of 16; 50%) followed by macroreentrant 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 macroreentrant 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 to 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 (Figure 3 and 4). In these cases, mapping with the linear catheter demonstrated significantly lower mean voltage amplitude that was coupled with highly fractionated and non-distinctive electrograms, limiting accurate activation 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 macroreentrant circuits and in the 2 focal arrhythmias. In 1 patient with macroreentrant 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% vs 33.4%; p=0.01). Moreover, the pacing threshold was lower using multielectrode-mapping catheters as 57.7% of pacing sites had threshold ≤10mA@2ms 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 3.5mm distal electrode and 1mm 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 3.5mm and 1mm electrode catheters with a 5th percentile of 0.48mV and 0.52mV, respectively; 2) mapping resolution within areas of low voltage and scar is enhanced with 1mm 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/or overdrive pacing techniques was more accurate using 1mm electrode catheters.

Three-dimensional (3D) 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 and Marchlinski, however limited data exist regarding the normal voltage distribution in the atria. Kapa et al have defined the normal bipolar voltage distribution in the left atrium using 3.5mm Thermocool® catheter. In 10 patients with paroxysmal AF, the mean bipolar voltage amplitude was 1.44±1.27mV, and 95% of all points demonstrated a bipolar voltage amplitude >0.45mV. Our study confirms this observation and extend 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 >0.48mV. In addition, we measured the distribution of electrograms duration in healthy atria and found that 95% of all electrograms had a duration < 58ms.

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 macroreentry but also sometimes microreentry involving preexisting 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 and colleagues have reported the feasibility to rapidly map and successfully ablate these arrhythmias using the Pentaray® multielectrode-mapping catheter in post-
PVI patients with ATs.\textsuperscript{11}

In this study, we established the normal atrial electrogram characteristics of 2 commonly used catheters: a standard mapping/ablation catheter (Thermocool\textsuperscript{®}) and a multielectrode-mapping catheter (Pentaray\textsuperscript{®}). While 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 electrical 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 0.5-4.0mV 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 due to the increased electrical “current” density at the electrode-tissue interface.

In addition, pacing from a multielectrode-mapping catheter placed in or around a macroneventric 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 reentry. Barbhaiya and colleagues have recently reported the utility of such approach to define the mechanism of atrial tachycardias.12

Study limitations
This study includes a relatively small cohort of patients. While mapping data with the linear catheter was confirmed by contact force measurement, such data was 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 to 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 was 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 3.5mm distal electrode (Thermocool®) and a multielectrode-mapping catheter with 1mm 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.

Conflict of Interest Disclosures: Elad Anter receives research grants and speaking honoraria from Biosense Webster and Boston Scientific. Mark E. Josephson receives research grants and speaking honoraria from Medtronic. Cory M. Tschabrunn has no relevant disclosures.

References:

European Heart Rhythm Association (EHRA), a registered branch of the European Society of Cardiology (ESC) and the European Cardiac Arrhythmia Society (ECAS); and in collaboration with the American College of Cardiology (ACC), American Heart Association (AHA), the Asia Pacific Heart Rhythm Society (APPRS), and the Society of Thoracic Surgeons (STS). Endorsed by the governing bodies of the American College of Cardiology Foundation, the American Heart Association, the European Cardiac Arrhythmia Society, the European Heart Rhythm Association, the Society of Thoracic Surgeons, the Asia Pacific Heart Rhythm Society, and the Heart Rhythm Society. *Heart Rhythm.* 2012;9:632-696 e21.


Table 1: Baseline Patient Characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Validation group (n=10)</th>
<th>Scar-related atrial arrhythmias (n=20)</th>
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<td>Age, y</td>
<td>55.2±9.3</td>
<td>64.2±11.3</td>
</tr>
<tr>
<td>Gender, male</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. 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>
</tr>
<tr>
<td>Surgical MV replacement</td>
<td>0 (0)</td>
<td>6 (30)</td>
</tr>
<tr>
<td>Presenting arrhythmia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paroxysmal AF</td>
<td>10 (100)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Persistent AF</td>
<td>0 (0)</td>
<td>6 (30)</td>
</tr>
<tr>
<td>AT</td>
<td>0 (0)</td>
<td>14 (70)</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SD, median (range) or n (%). AADs=antiarrhythmic drugs; AF=atrial fibrillation; AT=atrial tachycardia LA=left atrium; LVEF=left ventricular ejection fraction; MV=mitral valve.
**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) (linear vs. multielectrode-mapping catheter)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total low voltage area &lt;0.5mV (cm(^2))</strong></td>
<td>20.4cm(^2) [9-55cm(^2)]</td>
<td>14.7cm(^2) [7-48cm(^2)]</td>
<td>0.02</td>
</tr>
<tr>
<td>(median, 25%, 75%)</td>
<td>22, 14, 50</td>
<td>15, 9, 43</td>
<td></td>
</tr>
<tr>
<td><strong>Intermediate area 0.25 - 0.5mV (cm(^2))</strong></td>
<td>6.1±5.9</td>
<td>10.2±4.3</td>
<td>0.02</td>
</tr>
<tr>
<td>(median, 25%, 75%)</td>
<td>5.2, 3.8, 9.9</td>
<td>8.8, 4.7, 11.6</td>
<td></td>
</tr>
<tr>
<td><strong>Dense scar &lt;0.25mV (cm(^2))</strong></td>
<td>14.2±8.1</td>
<td>4.3±3.6</td>
<td>0.01</td>
</tr>
<tr>
<td>(median, 25%, 75%)</td>
<td>16.6, 10.2, 18.5</td>
<td>4.0, 2.1, 6.8</td>
<td></td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SD, range [  ]
Figure Legends:

**Figure 1:** Left atrial bipolar voltage maps (0.10-0.50mV) in the posterior-anterior view recorded with a standard linear catheter (panel A) and a multielectrode catheter (Panel 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 >0.5mV. In contrast, in a patient with scar-related atrial tachycardia, the bipolar voltage amplitude measured with the linear catheter (Panel C) was significantly lower than the one measured with the multielectrode catheter (Panel D).

**Figure 2:** Left atrial bipolar voltage maps (0.10-0.50mV) in the anterior-posterior view recorded with a multielectrode catheter (Panel A) and a linear catheter (Panel 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 peri-mitral area. The two catheters were then placed in contact with the zone of presumed “scar” as recorded with the linear catheter but not with the multielectrode catheter (Panel C). The mean bipolar voltage amplitude recorded with the multielectrode catheter at this location was 1.15 ± 0.7mV with mean electrogram duration of 42 ± 11msec and minimal fractionation (Panel D), suggestive of non-scar tissue.

**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 (Panel A) and a standard linear catheter (panel 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 025mV, 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 (Panels 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 (Panel E). When the multielectrode catheter was placed over the isthmus, >75% of the tachycardia cycle length was recorded at this single point acquisition (Panel F). The tachycardia terminated with ablation at this site.

**Figure 4:** In a patient with macroreentrant 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 9gr of tissue contact force. The multielectrode catheter was positioned parallel to the tissue (panel A). While the linear catheter recorded low, far-field, signal with amplitude of 0.12mV, the multielectrode catheter recorded sharp, near-field, signals with bipolar amplitude range of 0.18-0.28mV that allowed both local time annotation and pacing with capture (Panel B).

**Figure 5:** In a patient with history of surgical maze, two 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 <0.5mV, limiting activation and entrainment mapping (Panel A right). When the multielectrode catheter was placed at the peri-mitral area alongside the linear ablation catheter, fractionated mid diastolic
electrograms with bipolar voltage amplitude range of 0.18-0.34mV were recorded (Panel A left). 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 13ms longer than the tachycardia cycle length. A linear ablation between the mitral valve and the left inferior pulmonary vein terminated the tachycardia.
High-Resolution Mapping of Scar-Related Atrial Arrhythmias Using Smaller Electrodes with Closer Interelectrode Spacing
Elad Anter, Cory M. Tschabrunn and Mark E. Josephson

Circ Arrhythm Electrophysiol. published online March 19, 2015;
Circulation: Arrhythmia and Electrophysiology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-3149. Online ISSN: 1941-3084

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