Selection of Critical Isthmus in Scar-Related Atrial Tachycardia Using a New Automated Ultrahigh Resolution Mapping System

Decebal Gabriel Laţcu, MD; Sok-Sithikun Bun, MD; Frédéric Viera, MD; Tahar Delassi, MD; Mohammed El Jamili, MD; Alaa Al Amoura, MD; Nadir Saoudi, MD

Background—Accurate activation mapping of reentrant scar-related atrial tachycardias (AT) allows efficient radiofrequency ablation by targeting the critical isthmus (CI). We aimed to assess the electrophysiological properties of CI channels during mapping with the IntellaMap Orion basket and the Rhythmia system.

Methods and Results—We prospectively studied 33 AT (post–atrial fibrillation ablation or surgical mitral valve repair). The noise of bipolar electrogram (EGM) was systematically measured at 10 prespecified sites, as well as on a standard catheter and on the surface ECG. Bipolar EGM of CI regions were analyzed for amplitude, duration, and conduction velocity. The isthmus region to be targeted was chosen based solely on propagation. For each AT, 25 EGMs were automatically annotated. Noise of the Orion EGM was 0.011±0.004 mV, lower than that of a standard catheter (0.016±0.019) and surface ECG (0.02±0.01; P<0.05). For reentrant AT, within the CI, bipolar EGM amplitude (0.08±0.11 mV) and conduction velocity (0.27±0.19 m/s) were lower than those orthodromically before (0.62±0.93 mV; 1±0.49 m/s) and after (0.80±1.59 mV; 1±0.73 m/s) the isthmus (P<0.001 for all). In 97% of AT, ablation at the CI resulted in AT termination. No complications occurred.

Conclusions—This new automated ultrahigh resolution mapping system produces low noise and allows accurate diagnosis of AT circuits. CI on reentrant scar-related AT showed much lower EGM amplitude with a significantly slower conduction velocity than the surrounding parts of the circuit. Ablation of the areas of slow conduction resulted in a high acute success. (Circ Arrhythm Electrophysiol. 2017;10:e004510. DOI: 10.1161/CIRCEP.116.004510.)

Key Words: atrial tachycardia • atrial fibrillation • critical isthmus • iatrogenic • mapping

Scar-related atrial tachycardias (AT), either post–atrial fibrillation (AF) ablation or incisional, are very challenging arrhythmias. Critical areas of arrhythmogenesis occur often in diseased tissue where voltage is attenuated often below the background noise (BGN). ECG-based diagnosis, electroanatomic mapping, entrainment mapping, imaging of the substrate, and detailed knowledge of previously created lesions are all used in the diagnosis of the circuit (or the site of origin in case of focal propagation). Nevertheless, these techniques are time-consuming and challenging and at times yield confusing results. Electroanatomic mapping depends on technology with recent and significant advances in mapping resolution.1

See Editorial by Pathik and Kalman

The new Rhythmia (Boston Scientific) mapping system uses a 64-pole basket mapping catheter (IntellaMap Orion; Boston Scientific), which incorporates small unidirectional electrodes (0.4 mm²; 2.5 mm spacing) to suppress noise and farfield signals.2 Multielectrode acquisition and highly reliable automatic annotation yield maps with a previously unattained resolution.2–5 Ideally, complex circuits require ablation of a critical isthmus (CI), sometimes common to several reentry loops, to obtain immediate and definitive interruption of AT. CI may be difficult or even impossible to visualize in severely scarred areas with the currently available mapping tools, but are often sites of narrowing or slowing of the wavefront. We studied the results of mapping with Rhythmia in postlesion AT with the objective of finding the electrophysiological properties of the CI channels.

Methods

Consecutive patients who underwent radiofrequency (RF) ablation for scar-related AT with Rhythmia at the Centre Hospitalier Princesse Grace (Monaco) between April 2015 and February 2016 were prospectively included. The study was approved by the institutional committee on human research. According to institutional guidelines, all patients were informed and gave their written consent for the invasive procedures and the study. Antiarrhythmic drugs (other than amiodarone) were withdrawn at least 5 half-lives before the procedures (amiodarone was interrupted 1 month before the procedure). All patients had a preprocedure echocardiographic assessment of
WHAT IS KNOWN
- Scar-related atrial tachycardia (post–atrial fibrillation ablation or incisional) are challenging arrhythmias, and current diagnostic techniques, especially electroanatomic mapping using standard ring electrode catheters and entrainment, are time-consuming and at times yield confusing results.
- Ideally, complex circuits require ablation of the smallest possible number of critical isthmuses, sometimes common to several reentry loops, to obtain immediate and definitive tachycardia interruption, but they may be difficult or even impossible to visualize in severely scarred areas with currently available mapping tools.
- Very small unidirectional electrodes suppress far-field signals.

WHAT THE STUDY ADDS
- Automated ultrahigh resolution mapping with very small unidirectional electrodes produces low noise and allows accurate diagnosis of atrial tachycardia circuits.
- Critical isthmus of reentrant scar-related atrial tachycardia has much lower electrogram amplitude with a significantly slower conduction velocity than the surrounding parts of the circuit.
- Ablation of the areas of slow conduction resulted in a very high acute success.

Ablation Procedure
All procedures were performed with an uninterrupted anticoagulation regimen: vitamin K antagonists with a 2 to 3 international normalized ratio or direct oral anticoagulants with the last administration of the drug 12 (for dabigatran and apixaban) or 12 to 24 (for rivaroxaban) hours before the procedure. Taking an echo-guided right femoral venous approach, we performed coronary sinus (CS) catheterization with a decapolar diagnostic catheter (Inquiry L, 2-5-2 mm spacing; Saint Jude Medical) in the LA. An Agilis NxT steerable introducer (Saint Jude Medical) in the LA. Systemic anticoagulation with heparin bolus (target activated clotting time >350 s) was performed. Subsequent boluses of heparin were administered every 20 to 30 minutes if needed. Via a hep-arrinized Swartz SL0 sheath (Saint Jude Medical), an IntellaMap Orion mapping catheter was inserted in the right atrium (RA). Systematic RA mapping was first performed. In case of suspicion of an LA origin, after transseptal echocardiography to exclude an LA thrombus, a double transapical puncture was performed under transseptal echocardiography guidance, with insertion of the Orion catheter via the SL0 sheath and of a TactiCath Quartz 65 (Saint Jude Medical) via an Agilis NxT steerable introducer (Saint Jude Medical) in the LA.

Ultrahigh Resolution Electroanatomic Mapping
Detailed electroanatomic mapping of the RA and of the LA was performed using the bidirectional flexion with the basket in variable degrees of deployment (diameter ranging 3–22 mm). The location of each of the 64 electrodes is displayed on the mapping system using a combination of the magnetic sensor (located in the distal region of the catheter) and the impedance measurement of each basket electrode. Two reference electrograms (EGM; one main [R] and one additional [ΔR]) were chosen on the decapolar catheter. Cardiac beats were automatically selected for inclusion in the map based on cycle length (CL) stability, stable relative timing of 2 reference EGM, electrode location stability, and respiratory gating. The window of interest is automatically set by the system at the CL value and centered on the main reference EGM. For annotation of the local activation time of each acquired bipolar EGM, the system combines unipolar (maximum negative dV/dt) and bipolar (maximum amplitude) EGM. Fragmented or multiple potential EGM, the system takes into account the timing in the surrounding area to select the potential to use for the timing annotation. In case of a lack of statistical coherence between neighboring points in an area, no color code is displayed (the area is left gray). Scar setting may be finely tuned with the confidence mask tool (points in the immediate surrounding area with EGM bipolar amplitude below the confidence mask have no color code and are displayed in gray). The chamber surface geometry is generated using the location of the outermost electrodes, gated to the respiratory and cardiac cycles and updated continuously during mapping. Selection of the surface EGM is based on the projection distance (which may be set between 1 and 5 mm): only EGM recorded within the projection distance from the surface geometry are displayed. Activation and voltage maps were studied without changing the automatic timing annotation of the system.

Noise Assessment
Electronic noise was measured on the Rhythmia system on the acquired bipolar EGM during AT using the voltage caliper with adequate amplification and speed. BGN was assessed at 6 prespecified sites for the LA (midroof, midposterior wall, posterior mitral annulus, interatrial septum, midanterior wall, and appendage) and 4 prespecified sites for the RA (cavitricuspid isthmus [CTI], septum, appendage, and crista terminalis; Figure 1) for each map. The BGN was also assessed on the bipolar EGM recorded with the standard decapolar reference CS catheter (2 mm ring electrodes and spacing) and on the surface ECG.

Dense Scar Thresholding
After map completion, dense scar thresholding was performed wherever necessary to visualize the entire circuit. The confidence mask parameter was finely tuned for each map and lowered as much as needed (but above the BGN) for each AT (Figure 2).

Bipolar Voltage Map Assessment
For all LA maps, after exclusion of pulmonary veins (PV), the total LA surface was calculated using the surface measurement tool. We also measured the extent of the low voltage areas (for bipolar cutoffs of 0.5 and 0.05 mV; this corresponds to previously published and accepted data1), as well as the extent of the LA surface below the selected confidence mask for each map (Figure 3).

AT Diagnosis
Activation maps (both RA and LA) were studied for each AT. The right or the left origin was rapidly diagnosed based on the degree of CL coverage or by localizing the earliest activation site during the simultaneous display of both cavities in case of focal arrhythmias. Wavefront propagation was visualized by following a 10 ms window of activation, which was slowly advanced along the timescale (Movie in the Data Supplement). In opposition to previously available mapping systems, Rhythmia may display a circular window of interest, thus, eliminating the artificial early and late classification of local activation time, which is not appropriate for reentries. The isthmus region was chosen based solely on propagation (sites of narrowing or slowing of the wavefront). Because of much higher degree of resolution, we postulated that mapping would be of sufficient accuracy to
Critical Isthmus in Post-Scar Atrial Tachycardia

prevent misinterpretation. We routinely use entrainment mapping as a diagnostic technique with or without electroanatomic system, but elected not to do it in this initial series, to validate the above mentioned postulate.

As proposed since 2001, AT were classified in macroreentries and focal arrhythmias. Macroreentry was defined as AT propagating around a central obstacle (scar or anatomic structure—eg, a valve or PV ostia), with a ≥90% coverage of the CL within the chamber of origin (Figures 4 through 6; Figures I through III and Movie I in the Data Supplement). When there was no clearly distinguishable central obstacle (no central dense scar) or the potentials over a small area covered ≥90% of the CL, with a centrifugal activation of the remaining regions of the atria, the AT was considered a microreentry (as a mechanism of focal tachycardia; Figure 7). Purely focal AT were AT without coverage of the CL (<90%) and a centrifugal activation of the chamber from the earliest activation site (Figure 8).

Critical Isthmus Characteristics

Bipolar EGM of CI regions (defined as the narrowest or the slowest portion on the circuit, where RF ablation was applied) of reentrant AT were analyzed for amplitude, duration, and conduction velocity (CV). CV was measured offline by dividing the distance between successively activated points (in the direction of the main wavefront propagation) to time (the difference of the respective local activation time of 2 points situated in areas of visual homogenous CV; Figure 6). In this system, because of the very high-point density, this is equivalent to dividing the width of the area covered by activated points within a short (eg, 10 ms) time window to the time (Figure 6).
Critical Isthmus in Post-Scar Atrial Tachycardia

Ablation

Selection of the ablation target was solely based on circuit and isthmus visualization, without entrainment mapping. For focal AT, the site of earliest activation was targeted. In case of typical flutter, the CTI was ablated. Acute success was defined as termination of AT with sinus rhythm resumption or its change to another stable AT.
during ablation (without intervening atrial extrasystole). An ablation-induced transformation to another stable AT was presumed if there was an abrupt and sustained change in CL, intracardiac activation pattern, and surface ECG. Minor (eg, <10%) prolongation of CL alone, not accompanied by changes of the intracardiac activation pattern or surface ECG atrial wave morphology, was not considered as an acute success. If the AT was unchanged after CI ablation, this was considered a failure, and another target was chosen for ablation.

Conduction block was assessed across lines during pacing on one side while mapping on the other side with the Orion catheter to differentiate persistent but slowed conduction from a complete line block. The power setting was programmed at 20 to 35 W with an optimized catheter–tissue contact (between 10 and 40 g). RF was given in a point-by-point manner, without dragging, up to a force–time–integral at each site above 400 gs.

Additional ablation was performed if necessary for PV disconnection. Additional programmed stimulation and isoproterenol infusion was systematically performed. In case of supplemental AT in a given patient, remapping and ablation were performed up to sinus rhythm resumption.

Follow-Up
Patients were followed for clinical and asymptomatic recurrences. All patients had regular visits to the referring cardiologist with every 3 months 24 hours Holter monitoring during the first year postablation. Any recurring, sustained, symptomatic AT or AF was considered for a repeat procedure.

Statistical Analysis
Continuous variables are expressed as mean±SD. Median values and 25th and 75th percentiles are given in case of non-normal distribution. If clinically relevant, minimum and maximum values are also indicated. Numeric variables were compared with the t test or the Mann–Whitney–Wilcoxon test (in case of non-normality). Multiple group comparisons were performed using analysis of variance. Nominal variables were compared using the chi-squared test or Fisher's exact test, as appropriate. Correlation of numeric variables was assessed with the Pearson correlation coefficient. P<0.05 was considered significant.

Results

Patient Population
We prospectively studied 33 AT in 19 patients (6 women, median age 71 years, 25th–75th percentile 64–75 years; 1.65 AT/patient, maximum 4). Their CHA₂DS₂-VASc score was 2 (median; 25th–75th percentiles, 1–3). Hypertension was present in 55%, sleep apnea syndrome in 10%, ischemic heart disease in 10%, valvular cardiomyopathy in 25% (with mitral valve plasty in all), and 1 patient (5%) had hypertrophic cardiomyopathy. Left ventricular ejection fraction was preserved in all but 1 patient (median 62%; 25th–75th percentiles, 55–67). There was significant LA dilation: anteroposterior diameter (ultrasound) 44 (42–53) mm, surface (ultrasound) 22 (20–26) cm², volume (computed tomography scan) 131 (111–156) mL.

Previous Atrial Lesions
Of these 33 AT, 26 (78%) occurred on RF-related scars (post-AF: paroxysmal 5, persistent 21, with associated AT ablation in 12), 5 (15%) after previous surgical mitral valve repair, and 2 (6%) after both. The institutional strategy for AF ablation has been described elsewhere.10 In brief, ablation strategy was circumferential lasso-proven antral PV isolation in paroxysmal AF. A stepwise approach is used in persistent AF patients, with additional lesions targeting fractionated EGMs in the LA, inside the CS, and in the RA, as well as in LA roof and in some cases left isthmus lines. In this series, previous RF lesions were circumferential PV disconnection (n=28), ablation of fragmented potentials (LA, n=13; RA, n=10), the roof line (n=11), the mitral line (n=11), RF lesions inside the CS (n=6), around the superior vena cava ostium (n=8), and the CTI line (n=22). Among the 7 AT (21%) in patients with previous surgical mitral valve repair, additional lesions had been performed in 5: surgical cryomaze (3) and surgical RF maze (2).

AT time of occurrence was variable but often late with respect to the scar-creating intervention: 32±42 months (median 11, 2 [minimum] to 216 [maximum] months).

Noise Assessement
BGN was low on all EGM acquired with the basket catheter, in both LA and RA, ranging from 10 to 12 μV (0.011±0.004

Figure 4. Dual loop reentry with a clockwise (CW) anterior wall (AW) small loop and a counter clockwise (CCW) mitral flutter (PMF). The common isthmus of the 2 loops is delineated superiority by the AW scar and inferiorly by the superior aspect of the mitral valve (colored regions between the 2 black dashed lines). AP indicates anterior view; and LAO, left anterior oblique.
mV), without significant differences between sites (Figure 1).
BGN was also low on bipolar EGM recorded with the decapolar catheter (0.016±0.019 mV) and on the surface ECG acquired on the Rhythmia system (0.02±0.01 mV). Nevertheless, BGN on decapolar catheter EGM and on the surface ECG leads were significantly higher than the BGN of the Orion EGM (P<0.0001).

LA Maps Size and Voltage
A majority of AT were in the LA (30/33). LA map volume was 151±35 mL, with a surface of 129±27 cm². There was good correlation between LA map volume and the LA volume on the computed tomography scan reconstruction (r=0.80, P<0.0001; Figure IV in the Data Supplement). Dense scar threshold (confidence mask) was established at 0.016±0.009 mV (median 0.015 mV). The overall extent of low-voltage areas was important (58±25% of the LA surface was <0.5 mV; 22±16%, <0.05 mV; and 12±8%, <dense scar threshold; Figure 3).

AT Diagnosis
For each map, 25 684±14 276 EGM (mapping points) were acquired in 20±8 minutes. Because of the high number of electrodes on the mapping catheter (64), the number of AT beats used during mapping was 2286±1380 (9% of the EGM number). Point density was 209±128 points/cm². They were situated within 3.3±1.1 mm (2 [minimum] to 5 [maximum] mm) of the atrium shell.

Figure 5. Three different atrial tachycardias (AT) appearing successively in the same procedure in a 77-year-old woman with a past medical history of mitral valve plasty and surgical cryoablation around the pulmonary vein (PV) and at the base of the LA appendage (LAA). AT1 (upper) was a clockwise typical (CTI-dependent) flutter (cycle length [CL] 250 ms; right atrium [RA] not shown); the septal view of the left atrium (LA; A) shows a centrifugal activation starting from the septum; B, an infero-septal view of the LA, showing an activation starting from the fossa ovalis and turning around a scar area located underneath the right inferior PV, with a small anterodorsal arm. C, An anteroseptal view of the LA, showing the same centrifugal activation from the fossa ovalis turning around an anterior scar at the base of the LAA, with an anterodorsal arm. After ablation of the CTI, AT2 occurred (left inferior panel, CL 401 ms), which was a macro-reentry turning around the inter- septal scar (gray area) and a block region defined by a double black line; septal and posterior views of the LA are shown as it was impossible, owing to the local anatomic configuration as well as to the size of the macro-reentrant circuit, to display the entire circuit in a single view. After ablation of the posterior isthmus, AT3 occurred (right inferior panel, CL 450 ms), which was an anterior wall macro-reentry around the scar (gray area) at the base of the LAA (antero-septal view of the LA is shown). Ablation of the slow-conducting narrow isthmus between the scar and the left inferior pulmonary vein (LSPV) re-established sinus rhythm (SR). Both AT2 and AT3 were predictable (as potential circuits) by the LA map during the RA flutter (AT1); the presence of antidromic wavefronts suggests entrainment of AT2 and AT3 during the faster AT1. CTI indicates cavotricuspid isthmus; LI, left inferior; LS, left superior; PV, pulmonary vein; RI, right inferior; and RS, right superior.
Tachycardia CL ranged between 201 and 532 ms (289±79 ms). There was no correlation between the CL and the chamber volume. Mapping tended to be faster (19 versus 24 minutes; P=0.12) in the case of a shorter CL (<350 ms), because of faster beat acquisition.

Activation mapping revealed 26 macroreentries (78%), 4 (12%) microreentries, and 3 (9%) focal AT (Table and Figures 4 through 8; Figures I through III and Movie in the Data Supplement). A majority of the macroreentrant AT were perimitral flutter, roof-dependent, or double-loop reentries, including a roof or a perimitral circuit. Nevertheless, almost one third of LA macroreentrant AT (7/24, 29%) were unusual, either strongly suspected of using the vein/ligament of Marshall epicardially, or situated in the anterior/septal wall. Vein/ligament of Marshall was not cannulated but strongly suspected in 2 cases, where a tiny activity propagated independently from the surrounding LA endocardium. This was ascending in one case to activate the endocardium in the superior part of the LA appendage–left pulmonary vein ridge and descending in the other case. Patients with previous atrial incision developed only macroreentrant AT (5 LA: 3 perimitral, 1 in the septum, and

Figure 6. Anterior wall (AW) macroreentry. Anteroposterior (AP) view of the left atrium (LA) shows wavefront propagation by following a 10 ms window of activation advanced along the timescale (A, B, and C). Narrowing of the 10 ms wavefront (B) is suggestive of a slowing of the conduction (the 10 ms wavefront width is measured between the yellow dashed lines). Site labeled 2 was the critical isthmus (CI), which was successfully targeted (a block line was created between the central scar and the superior aspect of the LA appendage [LAA]–left pulmonary vein [PV] ridge because the patient had a previous circumferential PV isolation). Bipolar electrogram (EGM) amplitude and calculated conduction velocity (CV) are the smallest at the level of the CI (2) than orthodromically before (site 1) and after (site 3) the CI.

Figure 7. Microreentrant mechanism of a focal tachycardia in the posterosuperior LAA. Local fragmented potentials cover almost the entire cycle length (CL; 91%) on a small surface (23 mm²—delineated by a yellow dashed line). There is no discernable central obstacle. From this region, the LA (displayed in a posterosuperior view) is activated centrifugally. LAA indicates left atrial appendage; LI, left inferior; LS, left superior; PV, pulmonary vein; RI, right inferior; and RS, right superior.
1 in the anterior wall; and 2 RA: 1 CTI-dependent and 1 in the lateral wall).

Interestingly, microreentry/focal AT (n=7) were in only 1 case PV dependent. For focal AT, the amplitude of the bipolar EGM at the site of origin ranged from 0.133 to 0.265 mV, with a duration of 82 to 146 ms. The surface of microreentries (n=4) spanned from 0.25 to 1.5 cm² (Figure 7). Microreentrant AT had in 3/4 low bipolar voltage at the reentry site (0.017, 0.049, 0.192, and 1.54 mV).

Analysis of wavefront propagation also revealed in 34% of cases, dead-end pathways (excluding propagation inside PV). In 10 cases, potential circuits (different from the mapped AT) were visualized (Figure 5). Once the active AT was interrupted, in 2 cases, the potential circuits previously visualized became active (and subsequently ablated).

### Critical Isthmus Characteristics

For macroreentries, the sole visualization of the propagating wavefront allowed selection of the CI in all cases. This was always a region of significant narrowing or slowing of the wavefront. In case of coexistence of several slowing areas along the circuit, the slowest site (with the lowest CV) was defined as the CI because it was assumed that it was critical for AT maintenance.

Bipolar EGM amplitude at the level of the CI (0.08±0.11 mV) was much lower than the EGM amplitude along the AT circuit orthodromically before (0.62±0.93 mV; *P*=0.0001) and after the CI (0.80±1.59 mV; *P*=0.0001; see Figure 6). In 13 cases (50%), bipolar EGM amplitude at the level of the CI was <0.05 mV, and in 7 AT (27%), it was <0.03 mV. Maximal duration of bipolar EGM at the level of the CI for each AT was 100±63 ms and covered 35±18% of the CL.

Slowing of electric conduction was significant at the level of the CI: CV was 0.27±0.19 m/s, lower than orthodromically before (1±0.49 m/s; *P*<0.0001) or after the CI (1±0.73 m/s; *P*=0.0001; see Figure 6). Propagation visualization of the entire circuit showed in 17 AT (65%), a second slowing region (but at a lower extent or situated outside a narrow site).

### Result of Ablation

In 3 cases, AT stopped spontaneously, but the CI which had been visualized was ablated. For the remaining 30 AT, acute ablation success was 97% (in 20 cases by sinus rhythm resumption and in 9 cases by change into a different AT, subsequently mapped and ablated; the only failure concerned a perimital flutter were epi-endocardial ablation at the mitral isthmus failed). Time to AT termination was short but varied widely between 2 s of RF application to several minutes in case of wide isthmuses.

### Global Procedural Parameters

The global procedure time was 257±64 minutes. In the later cases, there was a significant shortening of the procedure time because of the learning curve (272±54 minutes for the first 10 cases versus 218±38 minutes for the last 10 cases; *P*=0.03; Figure V in the Data Supplement). This includes a particularly detailed point acquisition and the data analysis time, in the context of an institutional research program of arrhythmia mapping of advanced pathological atria. Fluoroscopy time was 18±10 minutes. RF delivery time was 1060±716 s. No complications occurred.

### Follow-Up

Patients were followed for clinical and asymptomatic recurrences for 12 (median) months after the index procedure.
Critical Isthmus in Post-Scar Atrial Tachycardia

An arrhythmia recurrence was documented in 8 patients (42%) after 2 months (25th–75th percentiles, 1.5–3 months; minimum 3 weeks to maximum 4 months). All recurrences but 1 were left AT other than the AT mapped and ablated during the initial procedure (the only recurring identical AT was a focal AT from the posterior LA appendage, for which the initial procedure was performed with a former Rhythmia software version without the possibility of anatomic correction of the extrapolation between the LA appendage and the left PV; thus, during the initial procedure, the localization of the site of origin was not accurate). PV isolation and block across previous lines were confirmed in all cases at the moment of the repeat procedure. With 1.4 procedures/patient, 11 months (median; 25th–75th percentiles, 7–14) after the last procedure, sinus rhythm maintenance rate was 84% (the 3 failure patients concern 1 patient with recurrent AT with a different ECG aspect, 1 who declined a repeat procedure for AT and for whom rate control was the final chosen strategy, and another patient with AF recurrences).

### Discussion

#### Main Findings

We are reporting the result of mapping and ablation of challenging postlesion (RF ablation or incisional) AT using a new ultrahigh resolution mapping system. Our results confirm that the basket catheter (IntellaMap Orion) records bipolar EGMs with low noise, allowing a low scar definition threshold setting. Thus, in severely scarred atria, this system is for the first time able to display low-voltage CIs, which are far below the current scar cutoff of classically available systems. For macroreentrant AT, new characteristics of the CI, such as much lower EGM amplitude and significantly slower CV than the surrounding parts of the circuit, are reported. The high rate of successful ablation based on the sole and simple circuit visualization and CI selection confirms the high degree of reliability of the automated and ultrahigh resolution mapping with this system.

#### Interpretation

The construction design of the mini-basket catheter is unique. The electrodes are flat and smaller (0.4 mm²) than those of any other diagnostic catheter that incorporates 1 mm ring electrodes (ie, PentaRay or Lasso; Biosense Webster, Diamond Bar, CA). This provides increased mapping resolution. Additionally, owing to their exclusive location on the external side of the spline, they are naturally less influenced by noise and far-field signals. Finally, as recently emphasized, the closer interelectrode spacing (center to center 2.5 mm for Orion versus 3 mm for PentaRay and 4.75 mm for standard 3.5-mm tip mapping catheters) allows recording of a higher bipolar voltage amplitude. It has also been reported that compared with Lasso, the mini-basket catheter has improved sensitivity in detecting PV potentials after RF ablation.

### Table. AT Diagnosis by Activation Mapping

<table>
<thead>
<tr>
<th>Type of AT (n=33)</th>
<th>Chamber (n)</th>
<th>Circuit/origin (n)</th>
<th>Detail (n)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro-reentry (26)</td>
<td>LA (24)</td>
<td>Perimital flutter (7)</td>
<td>CW (2), CCW (5)</td>
<td>Figure I in the Data Supplement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roof-dependent (6)</td>
<td>Posteroanterior roof activation (descending on the AW) (4)</td>
<td>Figure II in the Data Supplement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anteroposterior roof activation (ascending on the AW) (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dual loop reentry (4)</td>
<td>Anteroposterior roof activation (ascending on the AW)+CCW PMF (2)</td>
<td>Movie in the Data Supplement; Figure 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Posteroanterior roof activation (descending on the AW)+CCW AW (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reentry using the VOM (2)</td>
<td>CW AW reentry+CCW PMF (common isthmus anterior mitral valve) (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RA (2)</td>
<td>Free wall reentry (1)</td>
<td>Inferosuperior activation of VOM (1)</td>
<td>Figure 5—AT3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CW typical flutter</td>
<td>Superoinferior activation of VOM (1)</td>
<td>Figure 6</td>
</tr>
<tr>
<td>Micro-reentry (4)</td>
<td>LA (3)</td>
<td>AW/LAA</td>
<td>AW (2) (CL coverage 100%)</td>
<td>Figure 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LAA (posteroanterior; CL coverage 91%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RA (1)</td>
<td>CS ostium</td>
<td>CS ostium (CL coverage 92%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Focal (3)</td>
<td>LA (3)</td>
<td>RSPV / LAA</td>
<td>RSPV (1); CL coverage 50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LAA (posterior side) (2); CL coverage 53 respectively 76%</td>
<td>Figure 8</td>
</tr>
</tbody>
</table>

AT indicates atrial tachycardias; AW, anterior wall; CCW, counterclockwise; CL, cycle length; CS, coronary sinus; CTI, cavitricuspid isthmus; CW, clockwise; LA, left atrium; LAA, LA appendage; PMF, permitral flutter; PV, pulmonary vein; RA, right atrium; RSPV: right superior PV; and VOM, vein/ligament of Marshall.
Background Noise
We consistently found particularly low noise (0.011±0.004 mV) at all tested atrial sites. This is in accordance with previously published animal data (<0.01 mV in canine atria). Apart from fluoroscopy, our electrophysiology laboratory is equipped with a commercially available Bard recording system, the Rhythmia mapping system, a second mapping system (Carto3; Biosense Webster, for which the Patient Interface Unit is always on), and a magnetic navigation system (Sterotaxis, St. Louis, MN) coupled with Odyssey (Stereotaxis; integrating all the systems in a single display–keyboard–mouse interface). Other anesthesia equipment and the patient air heater are all usually on. All these represent potential sources of noise. The laboratory has not undergone any specific noise reduction work.

Low noise is mandatory for accurate dense scar detection. Preexisting linear lesions are detected as sharply demarcated lines of conduction block, manifested by an abrupt change in activation time and color, with double potential EGMs. Gaps within the lines are accurately visualized.2 In a ventricular scar animal model, scar detected by the Rhythmia system using the basket for mapping correlated best with the magnetic resonance imaging.5

We may consider that patients included in this series had extensive atrial scarring. Indeed, 58±25% of the LA surface was <0.5 mV. It may be argued that normal bipolar EGM amplitude recorded with the Orion catheter has not been reported, but a recent comparison of standard (3.5-mm tip) and high-resolution mapping with a smaller electrode catheter (PentaRay, 1 mm electrodes) showed similar fifth percentile activation window (<0.03 mV; activation mapping would not have been diagnostic of normal bipolar voltage distribution (0.50 versus 0.52 mV; P=0.80).6 The low noise that we are reporting here yielded the possibility of finely tuned scar-thresholding, with a dense scar threshold adapted in each case to visualize the entire circuit or the central scar; the mean value of the confidence mask (proprietary for scar threshold) in this series was 0.016±0.009 mV (median 0.015 mV). The previously reported values for delineating excitable dense scars in patients undergoing AF ablation have constantly been much higher (lowest 0.15 mV in the PV11). Interestingly, in our series, 50% of the AT had bipolar EGM amplitude within the CI of <0.05 mV and in 27% of <0.03 mV; activation mapping would not have been diagnostic in these cases with the higher bipolar scar threshold (such as 0.03 or 0.05 mV, which are generally used with other systems).

Mechanism Identification
With the increasing number of AF ablation procedures, the incidence of atypical LA flutter is constantly increasing. Various circuit sizes12–15 (or focal propagation) may occur, all being highly dependent on the previously created lesions.26 As expected, we found a majority of macroreentries (perimital flutter,11 roof-dependent flutters, or dual-loop reentry using both the roof and mitral isthmus, but few CTI dependent; Table). Nevertheless, unusual macroreentrant AT were more frequent (29%) than previously reported,9,13 and we found a significant number of microreentrannts and focal AT (21%), but with only one PV focal AT. Debate is still ongoing in the literature for precisely defining microreentry,7 localized reentry,14 or small reentry (diameter of the circuit <3 cm) and distinguishing them from macroreentry AT. We now consider that ultrahigh resolution/density mapping is the only appropriate tool for complete characterization of atrial depolarization; size assumption does not seem to be a prerequisite for the mechanism, but rather the lack of a distinguishable central scar. In the opposite case, in our opinion, regardless of the size of the central scar, which may be small and on top of its entrainable properties, AT could be classified as macroreentry, if the whole circuit can be mapped.

Critical Isthmus
We also report the hallmark characteristics of the CI: lower voltage and slower conduction, as previously suggested by seminal studies.18–20 Although CV mapping is not a clinically available tool,21 a correlation between EGM amplitude and CV has been reported only for RA flutters (logarithmic relationship).8 This suggested that CV is a more discriminative parameter than bipolar amplitude within low-voltage areas. Our calculations show that the electric propagation slows from 1±0.49 to 0.27±0.19 m/s at the level of the CI and accelerates afterward to 1±0.73 m/s (P<0001). While ultrahigh-density mapping allows quick and reliable calculations of the CV, visual assessment may be sufficient for clinical decision-making. In fact, wavefront propagation on Rhythmia may be visualized by following a short (eg, 10 ms) time window (of activation) along the timescale. Thus, the activated area is rather broad in normal (fast) CV regions, then becomes thin where CV diminishes and broadens again when CV increases (after exiting the CI; Figure 6). Repeated backward and forward shifts of the activation window may help to confirm the rapid initial visual impression.

AT diagnosis was based in our series only on activation mapping, and the CI (for macroreentries) was targeted with RF ablation. No correction of the timing annotation was needed because isolated wrong points (0.17% in animal study)2 do not influence the surrounding color of the map. To prospectively evaluate the mapping accuracy, we chose, only for this initial series, not to use entrainment maneuvers. Even if entrainment and postspacing interval mapping techniques may be difficult to perform and analyze because of high output pacing and lack of capture in areas of low voltage, this valuable electrophysiology tool should be systematically used in the setting of sustained organized tachycardias (eg, AT).

Limitations
The main limitations of our study are monocentric inclusions and the rather limited number of AT and patients. Nevertheless, the high accuracy of the activation mapping (100% correct diagnosis of the AT mechanism, as confirmed by ablation success) and the reproducible characteristics throughout the series (low noise, precise selection of the CI based on voltage, and CV criteria) validate ultrahigh-density mapping as the new gold standard for AT ablation, especially in scarred atria (post-AF ablation or incisional AT).

Lack of randomization and of a control group is another limitation. This was beyond our end point, but we were able to compare our findings to those of the recent historical series and
the more recent data based on multielectrode mapping with automatic annotation provided by other mapping systems.6

Conclusion
This new automated ultrahigh resolution mapping system allows, in severely scarred atria, accurate diagnosis of AT circuits and reliable localization of the CI, which consistently showed much lower EGM amplitude and significantly slower CV than the surrounding tissue and other parts of the circuit. As identified, ablation of isthmuses of slow conduction rapidly resulted in a high success rate. The low noise on the bipolar EGM recorded with the Orion basket catheter allows the low-scatter threshold setting.

Acknowledgments
Preliminary results of this study have been presented at HRS 2016 and Cardiostim 2016.

Disclosures
Dr Laçu and Dr Bun received consulting fees for Boston Scientific. The other authors report no conflicts.

References
Selection of Critical Isthmus in Scar-Related Atrial Tachycardia Using a New Automated Ultrahigh Resolution Mapping System
Decebal Gabriel Latcu, Sok-Sithikun Bun, Frédéric Viera, Tahar Delassi, Mohammed El Jamili, Alaa Al Amoura and Nadir Saoudi
**SUPPLEMENTAL MATERIAL**

**Supplemental figure 1.** A. Surface ECG and LA map showing a CCW macro-reentry around the mitral annulus. B. Surface ECG and LA map showing a CW macro-reentry around the mitral annulus in another patient. The red dotted lines encompass the 80 ms before the peak of the F wave in V1. LAO: left anterior oblique; LAA: left atrial appendage; PA: posterior view; CS: coronary sinus; LS: left superior, LI: left inferior; RS: right superior; RI: right inferior; PV: pulmonary vein.
Supplemental figure 2. LA maps and corresponding ECG’s showing roof-dependent macro-reentry in two patients. A. The activation wavefront is descending on the anterior wall (AW) and ascending on the posterior wall (PW). B. The circuit is ascending on the AW and descending on the PW.
**Supplemental figure 3.** Atypical (incisional) RA free wall AFL in a patient with previous mitral valve repair and RA incision. The RA origin is suggested by the negative flutter wave in V1. The activation map shows the CCW macro-reentry in the RA free wall around a central obstacle represented by the surgical incision (line of double potentials and block – black dashed line). Fragmented potentials are recorded in a narrow channel within the line of the incision scar. AP: anterior view.
Supplemental figure 4. Correlation between LA map volume and the LA volume on the CT-scan reconstruction ($r=0.80$, $p<0.0001$).
Supplemental figure 5. Procedure duration over time. In this study we systematically mapped both atria and remapped as many AT as necessary in each case (1.65 AT/patient, 1 to 4); if needed, PV isolation and remapping for block across eventual ablation lines were also performed.
Supplemental video. LA macro-reentrant AT. Wavefront propagation is visualized by following a 10ms window of activation that is slowly advanced along the timescale; the WOI is displayed in a circular view, encompassing the entire CL (438 ms in this example). Two opposite views of the LA are displayed; in order to facilitate propagation visualization tags (black dots) are displayed in two linear areas in the LA anterior wall where conduction block occurs. This AT is a dual-loop re-entry: roof dependent, ascendant on the anterior wall and CCW perimital variant (at a certain distance from the mitral annulus and the posterior wall); the narrowest common isthmus is located on the posterior wall (site of successful ablation).