Late Gadolinium Enhancement Magnetic Resonance Imaging Guided Treatment of Post–Atrial Fibrillation Ablation Recurrent Arrhythmia

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BACKGROUND: Macroreentrant atrial tachycardia (AT) accounts for 40% to 60% of recurrent atrial arrhythmias after atrial fibrillation (AF) ablation. To describe late gadolinium enhancement magnetic resonance imaging (LGE-MRI)–detected scar-based dechanneling as new ablation strategy to treat ATs after AF ablation.

METHODS: Data from 102 patients who underwent initial AF ablation and repeat ablation for recurrent atrial arrhythmia within 1-year follow-up were analyzed. All patients underwent LGE-MRI before initial and repeat ablation. Depending on the recurrent rhythm, patients with AF and AT recurrence were assigned to group 1 or 2, respectively. Group 1 underwent fibrosis homogenization as second procedure. Group 2 underwent LGE-MRI–detected scar-based dechanneling. Both groups underwent reisolation of pulmonary veins if necessary.

RESULTS: Forty-six patients (45%) presented with AF, and 56 patients (55%) presented with AT recurrence during follow-up after initial ablation. In the first 25 patients from group 2, the AT was electroanatomically mapped, and a critical isthmus was defined. It was found that those isthmus were located in the regions with nontransmural scarring detected by LGE-MRI. In the last 31 patients from group 2, an empirical LGE-MRI–based dechanneling was performed solely based on the LGE-MRI results. During 1-year follow-up after second ablation, 67% patients in group 1 and 64% patients in group 2 were free from recurrence (log-rank, P=1.000). In group 2, 64% in the electroanatomically guided and 65% in the LGE-MRI dechanneling group were free from recurrence (log-rank, P=0.900).

CONCLUSIONS: Anatomic targeting of LGE-MRI–detected gaps and superficial atrial scar is feasible and effective to treat recurrent arrhythmias post-AF ablation. Homogenization of existing scar is the appropriate treatment for recurrent AF, whereas dechanneling of existing isthmi seems the right approach for patients recurring with AT.

VISUAL OVERVIEW: A visual overview is available for this article.
Electrical isolation of the pulmonary veins (PVs) is the cornerstone for ablation of atrial fibrillation (AF), but success rates still remain moderate—60% to 80% for paroxysmal AF and 40% to 50% for persistent AF. To improve the outcomes, comprehensive efforts were made in the last years to develop new ablation strategies. This includes linear lesion sets, ablation of complex fractionated atrial electrograms, focal impulse and rotor modulation, ablation of left atrial (LA) low-voltage areas, and fibrosis homogenization. The common idea of all these ablation strategies is that the substrate for AF extends beyond the PVs and targeting these areas improves the success rate of maintaining sinus rhythm.

Despite improvement in ablation technology, imaging modalities, and ablation techniques, recurrence of atrial arrhythmias after AF ablation has not been overcome and still remains frequent. The underlying mechanisms are numerous and range from PV reconnection, gaps in prior ablation lines, nontransmural lesions, proarrhythmic effects of ablation techniques, development of non-PV triggers, and progression of the structural remodeling of the LA.

Gaps in prior ablation lines are the main cause of macroreentrant atrial tachycardias (ATs), which accounts for 40% to 60% of recurrence depending on the index procedure. Late gadolinium enhancement magnetic resonance imaging (LGE-MRI) is a noninvasive method to visualize and quantify the extent of LA fibrosis, which predicts the outcome after PV isolation (PVI). Besides LA fibrosis, LGE-MRI can also visualize and quantify ablation-induced LA wall scar and thereby identify those regions that may be responsible for arrhythmia recurrence.

In this study, we describe LGE-MRI–detected scar-based dechanneling as a new ablation strategy to treat macroreentrant ATs after AF ablation.

**METHODS**

One hundred and two patients from the University of Utah Atrial Fibrillation Database who underwent their first catheter ablation for paroxysmal or persistent AF between January 2011 and December 2016 with repeat ablation for recurrence of atrial arrhythmias within 1-year follow-up were consecutively included in this retrospective study. The protocol of the database is approved by the University of Utah Institutional Review Board. Written informed consent was obtained from all patients.

Patient information gathered for the purposes of the study was deidentified and protected in compliance with HIPAA (Health Insurance Portability and Accountability Act) regulations. All patients underwent transesophageal echocardiography before ablation to exclude LA appendage thrombus. All patients also underwent LGE-MRI study before ablation to assess the extent of LA fibrosis and 3 months after ablation to assess the extent of postablation LA scar. AF was classified as paroxysmal, persistent, or long-standing according to the 2017 HRS/EHRA/ECAS/APHRS/SOLACE Guidelines for the Management of Patients With Atrial Fibrillation (Heart Rhythm Society/European Heart Rhythm Association/European Cardiac Arrhythmia Society/Asia Pacific Heart Rhythm Society/Sociedad Latinoamericana de Estimulación Cardíaca y Electrofisiología). Depending on the recurrent rhythm present at the beginning of the second procedure, patients were divided into 2 groups. When the patient was in sinus rhythm at the beginning of the second procedure, atrial burst pacing was made to induce atrial arrhythmia. Forty-six patients who presented with AF recurrence were assigned to group 1; the remaining 56 patients with AT as recurrent rhythm were assigned to group 2 (Figure 1).

The data that support the findings of this study are available from the corresponding author on reasonable request.

**LGE-MRI Acquisition**

Magnetic resonance imaging studies were performed on a 1.5- or 3-Tesla clinical magnetic resonance scanner (Siemens Medical Solutions, Erlangen, Germany) using body and spine phased array receiver coils. LGE-MRI scan was initiated to 20 minutes following contrast agent injection (0.1 mmol/kg, Multihance; Bracco Diagnostic, Inc, Princeton, NJ) using a 3-dimensional inversion recovery, respiration-navigated, ECG-triggered, gradient echo pulse sequence. Typical acquisition parameters were free breathing using navigator gating, a transverse imaging volume with voxel size of 1.25×1.25×2.5 mm (reconstructed to 0.625×0.625×1.25 mm), and inversion time of 270 to 320 ms. ECG triggering was used to acquire a small subset of k-space data during stationary phase of the LA cardiac cycle. The other imaging parameters were optimized for respective field strength of scanner to improve fibrosis visibility and simultaneously keep scan duration acceptable.

**WHAT IS KNOWN?**

- Macroreentrant atrial tachycardia accounts for 40% to 60% of atrial arrhythmia after initial ablation for atrial fibrillation.
- Late gadolinium enhancement magnetic resonance imaging is a noninvasive imaging modality to visualize and quantify the distribution and extent of left atrial structural remodeling.

**WHAT THE STUDY ADDS?**

- We show in 102 patients with recurrent arrhythmia that late gadolinium enhancement magnetic resonance imaging is a feasible imaging modality to visualize and quantify the extent and distribution of ablation-induced scar.
- Compared with the conventional approach of an electroanatomical mapping–based ablation of recurrent arrhythmia after atrial fibrillation ablation, we show that an late gadolinium enhancement magnetic resonance imaging anatomically guided scar-based dechanneling as stand-alone procedure is feasible and associated with same outcomes in the treatment of recurrent atrial tachycardia.

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for patients (<15 minutes). For scans performed on 1.5-Tesla scanner: repetition time, 5.4 ms; echo time, 2.3 ms; and flip angle, 20°. For scans performed on 3-Tesla scanner: repetition time, 3.1 ms; echo time, 1.4 ms; flip angle, 14°. Typical scan time for the LGE-MRI study on 1.5/3-Tesla scanner was 8 to 12/5 to 9 minutes depending on subject heart rate and respiration pattern.

Quantification of Preablation Structural Remodeling/LA Volume/Postablation Scar

Quantification of LA remodeling was obtained using methods described elsewhere. Briefly, the LA wall was manually segmented by expert observers from the LGE-MRI images using the Corview image processing software (MARREK, Inc, Salt Lake City, UT). Fibrosis was defined by expert inspection, using an intensity threshold between 2 and 4 SDs above normal tissue.

Quantification of ablation-induced LA injury was performed using previously described methods on postablation images (>3 months post-ablation). Briefly, normal and injured tissue were defined based on a bimodal distribution of pixel intensities within the LA wall. The first mode of lower pixel intensities was chosen as normal tissue. Injured tissue was defined at 1 to 5 SDs above the normal tissue mean pixel intensity based on expert inspection.

LA wall injury was further evaluated for lesion depth analysis. To determine lesion depth at the LA wall surface, projection rays perpendicular to the LA wall surface are followed through the LA wall thickness and the extent of voxels marked enhanced and their size are measured. Three categories of lesion depth are defined: superficial (<1 mm), moderate (1–2 mm), and extensive (>2 mm).

Initial Ablation Procedure for AF

The details of PVI in addition to fibrosis-targeted ablation have been described elsewhere. In brief, the LA was accessed through 2 transseptal punctures under intracardiac echo guidance using a phased array catheter (Acunav; Siemens Medical Solutions USA, Inc, Mountain View, CA). A 10-pole circular mapping catheter (Lasso, Biosense Webster, Diamond Bar, CA) and a 3.5-mm thermocool ablation catheter (Biosense Webster) were advanced into the LA for mapping and ablation. A 14-pole catheter (Biosense Webster) was used to record right atrial and coronary sinus (CS) electrograms and was also used as the reference catheter for 3-dimensional electroanatomical mapping with CARTO (Biosense Webster). Radiofrequency energy was delivered with 50 W at a catheter tip temperature of 50°C for no longer than 5 seconds. Ablation lesions were placed in a circular fashion in the PV antral region until electrical isolation of the PVs, confirmed by Lasso catheter, was achieved. LA fibrosis homogenization was performed dependent on the degree and spatial distribution of LA fibrosis. Additional linear lesion sets were made at the mitral isthmus, roof, or the anterior wall at physicians’ discretion. Procedural end point was lack of AF/AT inducibility with high-dose isoproterenol and CS burst pacing down to 200 ms, in addition to abolition of PV potentials.

Recurrent Arrhythmia Type

AF was defined as a beat-to-beat variability in cycle length and morphology with irregular fibrillatory waves on surface ECG. AT was defined as a stable and regular atrial activation with a consistent endocardial activation sequence, an atrial cycle length of >180 ms, and a monomorphic P wave.
on surface ECG. Focal AT was defined by centrifugal activation from a localized region, whereas macroreentrant AT was defined by mapping of the entire cycle length of activity in a chamber with entrainment at ≥2 sites demonstrating a postspacing interval of <20 ms longer than the tachycardia cycle length. All ablation procedures were performed on therapeutic anticoagulation with warfarin or direct oral anticoagulants. Warfarin was continued post-procedure as well to maintain an international therapeutic ratio of 2.0 to 3.0.

Follow-Up and Definition of Recurrence
A postablation blanking period was observed for 3 months. Antiarrhythmic drugs were discontinued at the end of the blanking period. All patients were seen in the clinic at 3 months after ablation and followed up at 3-month intervals thereafter. Each patient received a 12-lead ECG and an 8-day Holter monitor for detection of arrhythmia recurrence postblanking period at 3, 6, and 12 months. Additional ECG recording was obtained as suggested by the patients' reported symptoms. Recurrence was defined as any documented atrial arrhythmia sustained for >30 seconds after the 3-month blanking period, according to the HRS consensus statement. Times for no recurrence of atrial arrhythmia were censored at day 365 after initial or second ablation.

Second Ablation Procedure for AT Recurrence
For patients presenting with AT as recurrent rhythm, a 14-pole catheter was advanced into the CS. When the patient was in sinus rhythm at the beginning of the procedure, atrial burst pacing was made to induce AT. If the AT was suggestive of left-sided origin, Thermocool ablation catheter was advanced into the LA for mapping and ablation. The 14-pole catheter in the CS was used to record CS electrogams and as the reference for 3-dimensional electroanatomical mapping with CARTO.

In the first 25 patients, mapping of the macroreentrant AT presented at the beginning of the procedure was electroanatomically guided using CARTO, and a critical isthmus or slow conduction zone was defined. Those isthmi were found in the regions with nontransmural (<1 mm) scarring detected by LGE-MRI. Radiofrequency energy was delivered at 50 W and with 50°C for no longer than 5 seconds targeting not only the isthmus identified by electroanatomical mapping but was also empirically delivered to areas of nontransmural scarring (<1 mm) on LGE-MRI (Figure 2), which may provide a critical isthmus for another AT with the goal of abolishing all LGE-MRI–detected isthmi. Lack of AT inducibility with high-dose isoproterenol and CS burst pacing down to 200 ms were also confirmed.

In the last 31 patients of patients with recurrent AT, the AT was not electroanatomically mapped. In these patients, an LGE-MRI–based dechanneling was performed solely based on the integrated LGE-MRI data, and procedural end point was the abolishment of all of the isthmi with areas of <1 mm transmural lesions. The order of the ablation of the channels was random and dependent on the distribution of the channels and the physician's discretion. Lack of AT inducibility with high-dose isoproterenol and CS burst pacing down to 200 ms were also confirmed.

Figure 2. An example of dechanneling procedure targeting channels/gaps and superficial lesion areas. A, Three-month postablation 3-dimensional late gadolinium enhancement magnetic resonance imaging of the left atrium shows the lesions (ablation scar) from the initial ablation procedure and the ablation lines performed during the second ablation procedure viewed from right posterior oblique (top) and right anterior oblique (bottom). Channels/gaps were identified at the anterior side to bottom of the right inferior pulmonary vein (RIPV) and the anterior wall (red circles). Ablation was performed at the channels/gaps and superficial lesions (red lines) during the second session. B, Lesion scale shows the extent of postablation scar (0–2.5 mm) by color ranging from healthy (blue) to superficial lesion (<1 mm, green to yellow) and extensive lesions (orange to red). C, The ECG (leads I, II, and V1) and the bipolar electrograms of ablation catheter and coronary sinus (CS) during ablation at the gap at the left atrial roof. The atrial tachycardia was terminated during ablation. ABL indicates ablation catheter; LAA, left atrial appendage; RIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein; and RSPV, right superior pulmonary vein.
Reisolation of PV was performed during the second procedure in any patient where gaps in prior ablation lines were detected by LGE-MRI, which resulted in electrical PVI.

Second Ablation Procedure for AF Recurrence

For patients presenting with AF as recurrent rhythm, reisolation of PVs was performed when electrical PV reconnection was detected. Subsequently, homogenization of residual fibrosis was performed. Lack of AF inducibility with high-dose isoproterenol and CS burst pacing down to 200 ms was also confirmed.

Statistical Analysis

Continuous variables are presented as mean±SDs, and a 2-sample t test was used for those to test for statistical significance. Categorical variables are presented as numbers and percentages, and Pearson χ² or Fisher exact tests were used for them to test for statistical significance as appropriate. An AF/AT recurrence survival curve was estimated by the Kaplan-Meier method and compared between groups 1 and 2 for second procedure using a log-rank test. Additionally, we compared the outcomes between the electroanatomically guided group and the nonelectroanatomically guided (LGE-MRI dechanneling) group using a log-rank test. Differences were considered significant at a P of <0.05.

RESULTS

Baseline Characteristics

One hundred and two patients (39 women; mean age, 66±11 years) were included in this study. Forty-six patients (16 women; mean age, 65±9 years) and 56 patients (23 women; mean age, 66±10 years) were assigned to group 1 and group 2, respectively. Tables 1 and 2 summarize the baseline characteristics of the whole study population, group 1 and group 2. No significant statistical differences were observed between the groups in terms of demographic data, extent of preablation LA fibrosis, and LA volume.

Based on the extent and the distribution of LA structural remodeling detected by 3-dimensional LGE-MRI, 28 patients received PVI alone as index procedure, 49 patients were treated with PVI and additional fibrosis homogenization, and the remaining 25 patients received LA linear lesion sets in addition to PVI and fibrosis homogenization during the initial procedure. Ten patients with documented typical atrial flutter received an additional cavotricuspid isthmus ablation.

After a 3-month blanking period following the index procedure, the mean time until documented recurrence for patients in group 1 was 159±49 days (median, 149 days; range, 111–204 days); for patients in group 2, the mean time was 144±57 days (median, 125 days; range, 109–165 days; P=0.146). Patients receiving LA linear lesion sets in addition to PVI and fibrosis homogenization presented significantly more likely with AT than AF as recurrent rhythm (Table 2). No significant differences regarding the recurrent rhythm were observed if the index procedure was PVI alone or PVI and fibrosis homogenization (Table 2).

Outcomes After Second Ablation

Patients with recurrence underwent a second ablation dependent on the recurrent rhythm. Group 2 under-
went LGE-MRI–detected scar-based dechanneling as new ablation strategy (Figures 2 and 3).

In the electroanatomically guided dechanneling group, AT was terminated in 8 patients during ablation of the first isthmus, in 8 patients during ablation of the second isthmus (anterior wall, mitral isthmus area), in 4 patients during ablation of the third isthmus (lateral wall, mitral isthmus area), and in 4 patients during ablation of posterior wall and the rest during ablation at the septal area between the right PVs. In 5 patients, termination occurred during delivering of lesions not at the critical isthmus defined by the CARTO system but rather in an adjacent and not distant channel.

In group 2, tachycardia terminated in 3 patients immediately after delivering the first lesion at an anterior wall and posterior wall/antral channel.

In total, 3 patients had their tachycardia either organized (group 1) or terminated (group 2) during dechanneling of an old circumferential lesion set. The number of dechanneled gaps varied between 8 and 15 in our study patients.

In accordance with former studies, 55% of patients experienced ATs as recurrent rhythm after initial ablation procedure.4,16,25 ATs were predominantly observed in

**DISCUSSION**

In this study, we demonstrate that targeting LGE-MRI–detected scar is a feasible approach during ablation of recurrent arrhythmia post-AF ablation. Further, we show that homogenization of ablation scar in patients with recurrent AT and dechanneling of existing isthmus in patients with AT are appropriate strategies to treat this group of patients. We also found that patients undergoing a more extensive initial AF ablation procedure were more likely to have AT as their recurrent arrhythmia.

Various approaches have been presented to treat patients with recurrent AT after failed ablation procedure. Homogenization of an existing scar has been shown to be successful in treating AF and ventricular arrhythmia.6,22,23 In this article, we present an approach that is based solely on LGE-MRI–detected scar. Akoum et al have demonstrated in retrospective analysis of the DECAAF I study (Delayed-Enhancement MRI Determinant of Successful Radiofrequency Catheter Ablation of Atrial Fibrillation) that covering initial fibrotic tissue with ablation lesions (homogenization) is a powerful predictor for procedural outcome. He hypothesized in his article that covering fibrosis eliminates existing arrhythmogenic channels that helps suppressing the sustainability of AF.24 Applying the same concept in homogenizing of an iatrogenic scar from previous ablation did help suppress recurrent AT and improve long-term outcomes in this group of patients.

In accordance with former studies, 55% of patients experienced ATs as recurrent rhythm after initial ablation for AF.4,16,25 ATs were predominantly observed in
patients who received linear LA lesion sets in addition to PVI and fibrosis homogenization in the index procedure. But we also saw around 20% of ATs after PVI only procedure without creating an LA substrate because of missing additional fibrosis homogenization. This could be due to a single gap in the isolation line and thus a focal trigger inside the PVs becomes active again. The antral isolation line around the PVs works then as the foundation of a macroreentrant AT. Besides recovery, residual gaps and missing transmurality of ablation lines lead to macroreentrant ATs as shown by Kobza et al. Some studies indicated that even after an endocardial and epicardial approach, it is often difficult to achieve a bidirectional block resulting in an increased risk for ATs as recurrent rhythm. Reasons for the difficulty to achieve a successful bidirectional block along LA lines lay in the anatomy of the LA, especially in differences of LA wall thickness ranging from 1 to 8 mm. Moreover, proximity to the circumflexus coronary artery or the CS are additional factors for failure of bidirectional block as they can serve as heat sink. Despite novel ablation strategies to improve the outcome, especially of patients with persistent AF, often extensive ablations in the LA are made. As shown in our results, the more extensive the ablation, the higher the probability for ATs.
as recurrent rhythm. Our goal for the initial ablation is homogenization of all fibrotic areas >1 cm. Linear lesion sets depend on extent and distribution of LA fibrosis detected by LGE-MRI and additional at physician’s discretion. Hence, the resulting scar can function as a new substrate for macroteentric tachycardia. After homogenization of the fibrotic tissue, too little residual fibrosis is left, which could serve as substrate for AF. Because of the substrate modification during the index procedure, multiple reentrant circuits in the

![Figure 4. Freedom from atrial tachyarrhythmia recurrence after second ablation procedure. Kaplan-Meier curve shows that there is no significant difference in the outcomes after the second procedure between the atrial tachycardia (AT) group and the atrial fibrillation (AF) ablation group (log-rank test, \(P=1.000\)).](image)

| Days | 0  | 50 | 100 | 150 | 200 | 250 | 300 | 350 | Survival |
|------|----|----|-----|-----|-----|-----|-----|-----|----------|
| AF   | 46 | 44 | 39  | 36  | 35  | 33  | 31  | 0.67 |
| AT   | 56 | 55 | 48  | 40  | 39  | 39  | 36  | 0.64 |

![Figure 5. Freedom from atrial tachyarrhythmia recurrence after second ablation procedure in group 2. Kaplan-Meier curve shows that patients in the nonelectroanatomically guided dechanneling group achieved the same outcomes with patients in the electroanatomically guided dechanneling group (log-rank test, \(P=0.900\)). AF indicates atrial fibrillation; AT, atrial tachycardia; and EAM, electroanatomic mapping.](image)

| Days | 0  | 0  | 100 | 150 | 200 | 250 | 300 | 350 | Survival |
|------|----|----|-----|-----|-----|-----|-----|-----|----------|
| Dechanneling | 31 | 30 | 29  | 22  | 22  | 22  | 20  | 0.65 |
| EAM + Dechanneling | 25 | 25 | 25  | 19  | 18  | 17  | 17  | 16  | 0.64 |
fibrotic tissue responsible for maintenance of AF are abolished, but, therefore, a substrate for macroreentrant tachycardias can be created. Those ATs represent often with an incessant character and because of relatively high ventricular response are poorly tolerated by the patient.\textsuperscript{30} The ablation approach for ATs as recurrent rhythm is challenging and associated with a wide range of success rates at follow-up. These patients present with a complex substrate in the LA, which consists of the scar from the index procedure in addition to residual or new fibrotic substrate. Identification of mechanism and circuit of these tachycardias is often difficult and operator dependent even with new technologies of electroanatomical mapping, entrainment, or intracardiac ECG.\textsuperscript{30–32} In the present study, an additional electroanatomical mapping was associated with similar outcomes when compared with the LGE-MRI anatomic-guided approach. Such an approach that is solely anatomic based would save time and effort spent on the extensive LA electroanatomical mapping and help standardize AT ablation procedure and make it objective.

**Conclusions**

Our initial set of data shows that homogenization and dechanneling as stand-alone strategies are associated with the same outcomes compared with the classic approach used to treat patients with recurrent AT. To the best of our knowledge, this is the first study to describe LGE-MRI anatomic-guided approach for treatment of patients with recurrent AT.

**Limitations**

This is not a randomized controlled study. Because of incomplete follow-up, we could have missed some asymptomatic recurrences. Only patients who were eligible for LGE-MRI study and had pre- and post-ablation LGE-MRI of good quality were included in the study cohort.

**ARTICLE INFORMATION**

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**Disclosures**

Dr Khomolovski reports equity interest and consultant honoraria from Marrek, Inc. A.K. Morris reports equity interest on Marrek, Inc. Dr Marrouche reports consulting fees from Abbott, Biotronik, Wavelet Health, Cardiac Design, Medtronic, Preventive, Vytronus, Biosense Webster, Marrek, Inc, and Boston Scientific; research funding from Abbott, Boston Scientific, GE Healthcare, Siemens, Biotronik, Vytronus, and Biosense Webster; ownership interest in Marrek, Inc, and Cardiac Designs; and has contracted research with Biosense Webster, Medtronic, St. Jude Medical, and Boston Scientific. The other authors report no conflicts.

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