Cardiac magnetic resonance–aided scar dechanneling: Influence on acute and long-term outcomes

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BACKGROUND Late gadolinium enhancement cardiac magnetic resonance (LGE-CMR) provides tissue characterization of ventricular myocardium and scar that can be depicted as pixel signal intensity (PSI) maps.

OBJECTIVE To assess the possible benefit of guiding the ventricular tachycardia (VT) substrate mapping by integrating these PSI maps into the navigation system.

METHODS In total, 159 consecutive patients (66 ± 11 years old, 151 men [95%]) with scar-related left ventricular (LV) VT were included. VT substrate ablation used the scar dechanneling technique. A CMR-aided ablation using the PSI maps was performed in 54 patients (34%). Procedural data as well as acute and long-term outcomes were compared with those of the remaining 105 patients (66%).

RESULTS Mean procedure duration and fluoroscopy time were 229 ± 67 minutes and 20 ± 9 minutes, respectively, without significant differences between groups. Both the number of radiofrequency (RF) applications and RF delivery time were lower in the CMR-aided group (28 ± 18 applications vs 36 ± 18 applications, \( P = .037 \), and 19 ± 12 minutes vs 27 ± 16 minutes, \( P = .009 \), respectively). After substrate ablation, monomorphic VT inducibility was lower in the CMR-aided than in the control group (17 [32%] vs 53 [51%] patients, \( P = .022 \)). After a mean follow-up period of 20 ± 19 months, patients from the CMR-aided group had a lower recurrence rate than those in the control group (10 patients [18.5%] vs 46 patients [43.8%], respectively, \( P = .002 \); log-rank \( P = .017 \)). Multivariate analysis found that CMR-aided ablation (hazard ratio, 0.48 [95% Confidence Interval (CI) 0.24–0.96], \( P = .037 \)) was an independent predictor of recurrences.

CONCLUSION CMR-aided scar dechanneling is associated with a lower need for RF delivery, higher noninducibility rates after substrate ablation, and a higher VT-recurrence-free survival.

KEYWORDS Cardiac magnetic resonance; Electroanatomic maps; Heterogeneous tissue channel; Left ventricular reconstruction; Ventricular tachycardia ablation

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Introduction

Substrate-based catheter ablation is an effective therapeutic option in patients with recurrent episodes of scar-related ventricular tachycardia (VT). However, data obtained from large series still show a high rate of recurrence after ablation, which highlights the need for further improvement of the ablation technique.

In recent years, late gadolinium enhancement cardiac magnetic resonance (LGE-CMR) has been attracting growing interest for use in the identification of the arrhythmic substrate, as it can provide not only scar quantification and location but also characterization, with an unprecedented precision. This scar tissue characterization can be depicted as color-coded PSI maps that have a reasonably high correlation with the electroanatomic maps (EAMs) obtained during the ablation procedures. The heterogeneous tissue channels (HTCs) depicted in the PSI maps have been related to VT isthmuses in the EAMs. These PSI maps obtained from high spatial resolution LGE-CMR can be imported into the navigation systems to aid the substrate VT ablation. However, even though several groups have reported the use of LGE-CMR images during the substrate VT ablation procedure, the possible benefits in terms of VT substrate ablation procedure requirements, acute results, and long-term outcomes have not been yet established.
Methods

Patient Sample
This is a prospective experimental nonrandomized study. Consecutive patients (n = 159) referred for catheter ablation of left ventricle (LV) scar-related sustained monomorphic VT were included. Eleven patients (7%) had undergone a previous failed VT ablation.

In 83 patients without contraindication (implantable cardioverter-defibrillator [ICD], claustrophobia, renal failure) (52%), a CMR study was performed prior to the procedure. In 29 patients (18%), the CMR image could not be postprocessed because it either was not obtained with the proper acquisition protocol or had poor image quality. In 54 patients (34%), PSI maps were obtained from a high-resolution 3Tesla LGE-CMR study and were imported into the navigation system to aid the VT substrate ablation. Procedure requirements, acute results, and long-term outcomes were compared with those of the remaining patients, for whom PSI maps were not imported into the navigation system.

The study complied with the Declaration of Helsinki. The local ethics committee approved the study protocol, and all included participants signed the informed consent.

LGE-CMR acquisition and processing
A CMR study was performed using a 3T scanner (Magnetom Trio, Siemens Healthcare, Erlangen, Germany). In patients without a previous ICD, the CMR study was performed within 1 month before the ablation procedure. In the 22 ICD carriers (41%), images were used from the CMR study performed immediately before implantation, as preimplantation imaging is our routine clinical practice. For acquisition details, see supplemental material. All LGE-CMR images were processed using a previously described approach. Full LV volume was reconstructed in the axial orientation and the resulting images were processed with ADAS-VT (Galgo Medical, Barcelona, Spain) software. After endocardium and epicardium were delineated semiautomatically, 5 concentric surface layers were created automatically, from endocardium to epicardium, at 10%, 25%, 50%, 75%, and 90%, respectively, of LV wall thickness. A 3-dimensional (3D) shell was obtained for each layer. PSI maps were obtained from LGE-CMR images, projected to each of the shells following a trilinear interpolation algorithm, and color-coded. To identify the scar areas, a PSI-based algorithm was applied to characterize the hyperenhanced area as scar core or border zone, using 40% ± 5% and 60% ± 5% of the maximum intensity as thresholds. Anatomic shells of the right ventricle and the aortic root were also obtained for image fusion purposes. All shells were exported as VTK files and imported into the navigation system (CARTO, Biosense Webster, Diamond Bar, CA), as shown in the Figure 1. In the PSI maps, HTC was defined as a continuous corridor of border zone surrounded by scar core or an anatomic barrier (mitral annulus) that connects 2 areas of healthy tissue.

Ablation procedure
The procedure was performed under conscious sedation. If epicardial access was anticipated, general anesthesia was used. An open-irrigated 3.5-mm tip ablation catheter (Navistar Thermocool, Biosense Webster) was used for mapping and ablation. A transseptal approach was used for LV endocardial mapping. The CARTO system was used for substrate mapping and ablation. In patients with a previous LGE-CMR study, an anatomic map of the aorta or the right ventricle was obtained and used to integrate the 3D LGE-CMR-derived reconstructions with the spatial reference coordinates of the CARTO navigation system.

Substrate VT ablation was performed according to the scar dechanneling technique in all patients. A 4-step ablation protocol was performed as previously described, as shown in Figure 2A. An endocardial or epicardial substrate map was acquired first. Electrograms with delayed components (E-DCs) were tagged and differentiated between inner and entrance conducting channel (CC) electrograms, depending on delayed-component precocity during sinus rhythm. The CC entrance was defined as the E-DC with the shortest delay between the far-field component of healthy or border zone muscle and local component corresponding to the local activation of myocardial fibers in the scar (Figure 1). Second, radiofrequency was delivered at target ablation sites, which were the CC entrances identified in the EAM, as described in the previous step. Third, a remap was acquired to document complete substrate elimination or to identify residual E-DCs if that were the case. Residual E-DCs were identified in the same way as in the first step, and RF ablation was delivered to eliminate all of them. Finally, a programmed ventricular stimulation was performed to induce residual VTs. If any residual sustained VT was induced, it was targeted for ablation either by activation mapping (if tolerated) or else by pace-mapping maneuvers. Inducibility was checked again after each residual VT ablation.

In the group of patients with a previous LGE-CMR study, substrate mapping was guided by the information from the 3D LGE-CMR-derived reconstructions (ie, PSI maps) integrated into the navigation system (after fusion with the aorta or the right ventricle anatomy). CCs observed in the EAM were considered the gold standard and became target ablation sites. Concordance between CCs observed in the EAM and HTCcs observed in the PSI maps was analyzed. Those with the same localization and orientation observed in both the EAM and PSI maps were considered as true positives. Those only observed in the EAM were considered as false-negatives, whereas HTC only identified in LGE-CMR-derived reconstructions were considered false-positives (Figure 2B). In all patients, the target ablation sites were the CC entrances identified in the substrate EAM.

Procedural success and follow-up
Acute success was defined as noninducibility of any sustained monomorphic VT at the end of the procedure.
Partial success was considered to be achieved when the clinical VT was successfully ablated but other monomorphic VTs remained inducible. Office visits for clinical evaluation and ICD interrogation were scheduled every 6 months. A first VT zone was programmed 10 beats per minute slower than the clinical VT heart rate. A monitor zone was also programmed. Any sustained VT, whether ICD intervention was required, was considered a recurrence during follow-up. A nonsustained VT was not considered a recurrence.

**Statistical analysis**

Continuous variables are presented as mean plus or minus standard deviation. To compare means of 2 variables, the t test, Mann-Whitney U test, or analysis of variance test was used, as appropriate. Categorical variables were expressed as total number (percentages) and compared between groups using the χ² test. The effect of different variables on (event-free) survival was investigated using the Cox proportional hazards model. Variables that showed a statistically significant effect on event-free survival in univariate analyses

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**Figure 1** Integration of LGE-CMR information into the navigation system. **A:** Inferior view of the endocardial bipolar voltage electroanatomic map from a patient with an ischemic scar. Electrograms with delayed components were classified as conducting channel entrance (black dots, 1 and 4) or inner conducting channel (blue dots, 2 and 3) points, depending on delayed-component lateness during sinus rhythm. Red dots show the radiofrequency application points. **B:** Signal intensity map obtained from late gadolinium enhancement cardiac magnetic resonance (LGE-CMR). Areas with hyperenhancement (dense scar) are coded in red, normal myocardium is coded in purple, and border zone is coded in blue-green-yellow. The heterogeneous tissue channel can be observed inside the scar. **C:** Registration of the electroanatomic map with the LGE-CMR reconstruction. Corridors formed by conducting channel points (blue and black dots) are present in the scar tissue.
were entered in a multivariate Cox proportional hazards model using a backward stepwise selection to obtain the final model. At each step, the least significant variable was discarded from the model, until all variables in the model reached a $P$ value $<.10$. Kaplan-Meier survival analysis was used to analyze the time to VT recurrence, and log-rank test was used to detect significant differences between groups. For all tests, a $P$ value $<.05$ was considered significant. Statistical analysis was performed using SPSS, version 18.0 (SPSS, Inc, Chicago, IL).

Results

From May 2009 to June 2015, a total of 159 patients (66 ± 11 years old, 151 men [95%]) were included in the study; 121 (76%) had ischemic heart disease. Baseline characteristics are summarized in Table 1. There were no statistically significant differences in age, sex, left ventricular ejection fraction (LVEF), New York Heart Association class or type of cardiomyopathy between patients in whom CMR was or was not used to guide ablation. Tachycardia cycle length was significantly shorter in the CMR-aided group (299 ± 145 ms vs 357 ± 106 ms, $P = .023$). There was no difference between the 2 groups with respect to substrate accessibility, defined as the optimal selected approach to potentially identify all the arrhythmogenic substrate. See supplemental material for details.20

Procedural data

In the whole study population, the mean procedure time was 229 ± 66 minutes and the mean fluoroscopy time was 20 ± 9 minutes. In the CMR-aided group, a mean of 15 ± 9 minutes was needed to perform the right ventricle or aorta mapping and the image integration. The mean time needed to build the LV map was 36 ± 16 minutes, with no significant differences between the CMR-aided group and the control group (36 ± 14 vs 34 ± 19 minutes, respectively; $P = .674$). The mean number of points obtained to build the EAM was 496 ± 278 and for the remap was 787 ± 326. A mean of 53 ± 41 E-DCs were identified as inner CC electrograms and 12 ± 11 were identified as CC entrance electrograms. The mean number of CCs identified in the EAM was 2.4 ± 1.6. An epicardial approach was performed in 49 patients (30%). There was no difference in any of these parameters between groups (Table 2).

In the CMR-aided group, 99 (77%) of the 129 CCs identified in the EAM matched with the HTCs identified in the PSI map; there were 30 false-negatives (23%). A total of 19 HTCs (16%) observed only in the PSI maps were considered false-positives. The target ablation sites were the CC entrance electrograms, as previously described.16 The percentage of CC entrance electrograms located in the color-coded bipolar EAM in a zone considered healthy tissue ($>1.5$ mV) was higher in the CMR-aided group than in the control group (26% vs 12%; $P = .008$). There was no difference between the 2 groups in the percentage of inner CC electrograms in the zone with bipolar voltage $>1.5$ mV in the EAM (14% vs 13%; $P = .842$). Total RF time (19 ± 12 minutes vs 27 ± 16 minutes, $P = .006$), as well as the number of RF applications (28 ± 18 vs 36 ± 18; $P = .037$), was lower in the CMR-aided group (Table 2).

Figure 2  A and B Scar dechanneling ablation protocol and the identification process for heterogeneous tissue channels or conducting channels.
**Table 1** Baseline characteristics (N = 159)

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CMR = cardiac magnetic resonance; DLP = dyslipidemia; DM = diabetes mellitus; HT = hypertension; IHD = ischemic heart disease; LVEF = left ventricle ejection fraction; LVEDD = left ventricle end-diastolic diameter; LVESD = left ventricle end-systolic diameter; NYHA = New York Heart Association class.

All continuous variables are presented as mean ± SD.

*P value <0.05.

**Acute outcomes**

Differences between groups in the acute results are summarized in Table 2. Interestingly, noninducibility of residual VT after substrate ablation was higher in the CMR-aided group (68%) than in the control group (49%); P = .022. However, there were no differences between groups in acute results after residual inducible-VT ablation. A total of 70 patients (44%) presented with residual VT after the substrate ablation. A mean of 1.7 ± 1.2 residual VTs were induced in this subgroup of patients. After residual inducible-VT ablation, noninducibility for any sustained monomorphic VT was achieved in 130 (82%) patients (Table 2).

Complications occurred in 14 patients (8.8%) without differences between groups (P = .462). There was no death related to the ablation procedure.

**Long-term outcomes**

The mean follow-up period was 20 ± 19 months, without differences between groups (P = .252). Nine patients (5.7%) died during the follow-up period (all of them from the control group, P = .023). Four patients died from advanced heart failure, 1 from sudden cardiac death, and 4 from noncardiac causes. One patient (0.6%) underwent cardiac transplantation due to heart failure.

During the follow-up period, 56 patients (35.2%) had a VT recurrence. The CMR-aided ablation group had a lower recurrence rate than the control group (10 [18.5%] vs 46 [43.8%], respectively, log-rank test = 0.017). The Kaplan-Meier graph is shown in Figure 3A. Patients with PSI maps displaying HTCs that were not observed in the EAM (considered to be false-positives) had a higher rate of recurrences.
during the follow-up (29% vs 14%, log-rank test = 0.027). Twenty-nine patients in the control group had a preprocedural CMR but PSI maps were not available. Therefore, late gadolinium enhancement distribution in the LV wall was the only information provided by the CMR and was used for procedural planning. These patients had a higher recurrence rate than that of the CMR-aided group (12 patients [41.4%] vs 10 patients [18.3%], respectively, P = .036) (Figure 3B).

Univariate and multivariate analyses were made to identify associated variables or independent predictors of recurrence during follow-up (Table 3). In the univariate analysis, substrate accessibility, LVEF, noninducibility of sustained monomorphic VT after scar dechanneling alone, and CMR-aided ablation were found to be associated with the probability of recurrences. Only substrate accessibility (hazard ratio [HR]: 0.493 [95% Confidence Interval (CI) 0.289–0.841], P = .009) and CMR-aided ablation (HR: 0.482 [95% Confidence Interval (CI) 0.243–0.958], P = .037) were independent predictors of recurrences during the follow-up.

Finally, these results are consistent with those of the subgroup analysis for ischemic and nonischemic patients. In ischemic patients, the CMR-aided ablation subgroup had fewer recurrences than the control group (7 [18.9%] vs 36 [42.8%], log-rank test = 0.05). In nonischemic patients, there was a trend to a lower recurrence in the CMR-aided subgroup (3 [17.6%] vs 10 [47.6%], log-rank test = 0.18). The Kaplan-Meier graphs for ischemic and nonischemic patients are shown in the supplemental material (Supplemental Figure 1).

Discussion
To the best of our knowledge, this is the first study reporting the benefit to acute and long-term outcomes of integrating LGE-CMR information with the navigation system to guide the substrate VT ablation. The use of PSI maps derived from LGE-CMR to guide the ablation minimized the number of RF applications and RF delivery time needed and was also associated with a higher rate of acute success after substrate ablation, suggesting better identification of the arrhythmogenic substrate and target ablation site. Consequently, patients in whom the substrate ablation is performed under the guidance of the PSI maps derived from the LGE-CMR have a significantly higher rate of survival free from ventricular arrhythmia recurrences.

The information obtained from the CMR showing the wall distribution of the scar contributes to deciding on the optimal approach (endocardial, epicardial, or combined), which could explain the better outcomes in the CMR-aided group compared with those in all other patients. However, a higher recurrence rate was also observed in control group patients that had a preprocedural CMR but no PSI integration, compared with that for the CMR-aided group. This difference could be explained by several factors associated with PSI integration into the navigation system: complete identification of the arrhythmogenic substrate; improved selection of the ventricular area to focus mapping; and better localization of the target ablation site, in this case the CC entrances (Supplemental Figure 2).

Acute results after scar dechanneling
Contrary to what might be expected, the use of PSI maps to guide substrate ablation does not reduce the total procedure or the fluoroscopy time. This finding is explained by the need to perform an additional map (the right ventricle or the aorta in this study) to integrate the 3D LGE-CMR reconstructions into the spatial reference coordinates of the navigation system. Creating this additional map takes time and is fluoroscopy guided (a mean of 15 minutes was added to the total procedure time). However, as there was no difference between the 2 groups of patients in total procedure or fluoroscopy time, the subsequent CMR-aided procedure reduced fluoroscopy use and the total procedure time.

Regarding the acute success after scar dechanneling alone, the CMR-aided ablation group had a lower rate of patients still inducible for any residual sustained monomorphic VT.
The scar dechanneling technique is based on identifying CCs and their entrances to target the ablation. Better delineation and characterization of the scar in the CMR-aided group could lead to more-accurate identification of CC entrances and consequently to more efficient and complete substrate elimination despite requiring less delivery of RF.

In this study, a higher number of CC entrances was observed in areas with bipolar voltage >1.5 mV when the ablation was guided by the PSI maps. Previous studies have suggested that the size of low-voltage areas in the EAM tends to be smaller than the scar areas in the LGE-CMR-derived maps, probably due to the far-field effect from healthy tissue that surrounds the scar; this is a bigger issue in small and heterogeneous scars. CMR-aided ablation could help to deliver radiofrequency applications as close as possible to the CC entrances, which are usually located at the scar border. In some cases, the CC entrances are hidden because of a high bipolar voltage of the far-field component on the EAM. Information obtained from LGE-CMR reconstructions may help to identify the path of the different HTCs and more accurately depict the entrances of the channel (Supplemental Figure 2). Consequently, more effective RF applications could be delivered closer to the actual channel entrance.

Long-term outcomes
The use of LGE-CMR to guide the VT substrate ablation is associated with a lower rate of recurrence during the follow-up. Our group recently reported that noninducible patients after scar dechanneling alone have a lower probability of VT recurrences or sudden death, and lower mortality, compared with patients requiring residual inducible-VT ablation, due to more complete substrate elimination. In the present study, patients in whom substrate ablation was guided by the PSI map information had less residual inducible VT after substrate ablation, probably due to a more-accurate identification and ablation of the substrate. Finally, patients with HTCs identified in the PSI map but not in the EAM had a higher rate of recurrence during the follow-up, suggesting that postprocessed CMR may identify arrhythmogenic substrate hidden in the EAM. Further studies are needed to confirm this observation.

Limitations
The main limitation of this study is the lack of randomization. As a result, patients in the control group had a more dilated LV and longer VT cycle length. Although these parameters were not independent predictors of VT recurrence in the multivariate analysis, we cannot exclude the possibility that having more advanced heart disease could have influenced outcomes. Contact force as well multielectrode catheters were not systematically used in this study. The size and depth of the ablation lesion were not evaluated, and therefore the influence of these parameters on the ablation outcomes cannot be analyzed. Utility of the LGE-CMR-aided ablation could be limited to patients without an implantable device. However, recent studies describe new promising techniques able to perform an LGE-CMR study in patients with an ICD. Ablation was delivered at CC entrances identified in the EAM. HTC entrances identified only by the PSI, without matching a CC on the EAM (false-positive), were not targeted for ablation. Therefore, the impact of guiding substrate ablation exclusively by PSI information cannot be analyzed in the present study. As CMR provides anatomic but not functional information, further studies are needed to understand the implication of HTCs identified only in the PSI map and not correlated with the EAM. Finally, all the structural abnormalities present in the scar tissue under the current spatial resolution of the CMR (1.4 × 1.4 × 1.4 mm) cannot be characterized, as previously reported.

Conclusion
CMR-aided scar dechanneling is associated with a lower need of RF delivery and higher rates of noninducibility after
substrate ablation and VT-recurrence-free survival. Randomized studies are needed to confirm these findings.

Appendix
Supplementary data
Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.hrthm.2017.05.018.

References