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iCONCEPTS

CONCEPTS ON THE VERGE OF TRANSLATION

Delayed-Enhanced MR Scar Imaging and Intraprocedural Registration Into an Electroanatomical Mapping System in Post-Infarction Patients

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Post-infarction arrhythmias are most often confined to scar tissue. Scar can be detected by delayed-enhanced cardiac magnetic resonance. The purpose of this study was to assess the feasibility of pre-procedural scar identification and intraprocedural real-time image registration with an electroanatomical map in 23 patients with previous infarction and ventricular arrhythmias (VAs). Registration accuracy and cardiac magnetic resonance/electroanatomical map correlations were assessed, and critical areas for VA were correlated with the presence of scar. With a positional registration error of 3.8 ± 0.8 mm, 86% of low-voltage points of the electroanatomical map projected onto the registered scar. The delayed-enhanced cardiac magnetic resonance–defined scar correlated with the area of low voltage ($R = 0.82$, $p < 0.001$). All sites critical to VAs projected on the registered scar. Selective identification and extraction of delayed-enhanced cardiac magnetic resonance defined scar followed by registration into a real-time mapping system are feasible and help to identify and display the arrhythmogenic substrate in post-infarction patients with VAs. (J Am Coll Cardiol Img 2012;5:207–10) © 2012 by the American College of Cardiology Foundation

Most post-infarction ventricular tachycardias originate from scar tissue and, therefore, its identification has been helpful in mapping and ablating these arrhythmias. Delayed-enhanced cardiac magnetic resonance (DE-CMR) precisely identifies scar tissue. The purpose of this study was to assess the feasibility of pre-procedural scar identification and segmentation from DE-CMR images and intraprocedural registration of the scar tissue with the electroanatomical maps (EAMs) obtained in real time.

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For this purpose, 23 consecutive patients (19 men; mean age 60 ± 12 years; ejection fraction 40 ± 13%) with post-infarction ventricular arrhythmias underwent DE-CMR before mapping and ablation of ventricular arrhythmias. All patients had a previous myocardial infarction (Tables 1 and 2). Radiofrequency ablation was performed for ventricular tachycardia (VT) in 10

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patients and for symptomatic premature ventricular complexes (PVCs) in 13 patients. No complications occurred. The study was approved by the Institutional Review Board of the University of Michigan.

The DE-CMR studies were performed on a 1.5-T magnetic resonance imaging scanner (Signa Excite CV/i, General Electric, Milwaukee, Wisconsin) with a 4- or 8-element phased-array coil placed over the patients' chests while in the supine position. Images were acquired with electrocardiographic gating during breath-holds. Dynamic short- and long-axis images of the heart were acquired using a segmented, k-space, steady-state, free-precession pulse sequence (repetition time, 4.2 ms; echo time, 1.8 ms; 1.4 × 1.4-mm in-plane spatial resolution, 8-mm slice thickness). Fifteen minutes after administration of 0.20 mmol/kg of intravenous gadolinium diethylenetriamine pentaacetic acid (Magnevist, Berlex Pharmaceuticals, Wayne, New Jersey), 2-dimensional DE-CMR was performed using an inversion-recovery sequence (1) (repetition time, 6.7 ms; echo time, 3.2 ms; in-plane spatial resolution, 1.4 × 2.2 mm, 8-mm slice thickness) in the short-axis and long-axis of the left ventricle at matching cine-image slice locations. The inversion time (250 to 350 ms) was optimized by visual inspection for optimal nulling of the normal myocardium. All patients had adequate CMR images as judged by the radiologist. The DE-CMR images were reviewed for the presence or absence of delayed enhancement by 2 observers before the actual mapping/ablation procedure.

ABBREVIATIONS AND ACRONYMS

DE-CMR = delayed-enhanced cardiac magnetic resonance

EAM = electroanatomical map

PVC = premature ventricular complex

VT = ventricular tachycardia

After informed consent was obtained, a 6-French quadripolar electrode catheter was introduced into the right femoral vein and positioned at the right ventricular apex. Programmed right ventricular stimulation with 1 to 4 extrastimuli was performed in all patients. Sustained VT was defined as VT lasting >30 s or requiring termination secondary to hemodynamic compromise.

Table 1. Baseline Clinical Characteristics of Patients

Age, yrs	60 ± 12
Male/Female	19/4
Ejection fraction, %	40 ± 13
Infarct age, yrs	8.8 ± 7.7
Infarct location	
Inferior	16
Anterior	6
Lateral	1
Targeted arrhythmia	
PVCs	13
VT	10
Antiarrhythmic therapy	7

Values are mean ± SD or n.
PVC = premature ventricular complex; VT = ventricular tachycardia.

Table 2. Characterization of Infarcts

Variable	PVCs	VT	p Value
n	13	10	
Infarct size, cm^3	12.44 ± 17.31	29.75 ± 13.93	0.03
% of LV mass	7.14 ± 7.59	17.16 ± 6.42	0.01
Subendocardial extent	13	10	
Degree of transmurality			
1%–25%	2	0	
25%–50%	7	2	
>50%	4	8	

Values are n or mean ± SD.
LV = left ventricular; other abbreviations as in Table 1.

In 10 patients, a total of 22 distinct sustained, monomorphic VTs (mean VT cycle length, 325 ms) were targeted.

A 3-dimensional mapping system (CARTO XP, Biosense Webster, Inc., Diamond Bar, California) with a 3.5-mm tip, open-irrigation ablation catheter (Thermocool, Biosense Webster) was used. For the mapping procedure, a bolus of 5,000 U of heparin was used initially, and heparin was then administered to maintain an activated clotting time of 300 s.

The intracardiac electrograms were filtered at 50 to 500 Hz and displayed along with leads V_1, I, II, and III on an oscilloscope at a speed of 100 mm/s. A left ventricular voltage map was generated with 235 ± 108 endocardial points during sinus rhythm.

Low voltage was defined as a bipolar voltage amplitude ≤1.5 mV (2). The regions with bipolar voltage ≤1.5 and ≤1.0 mV were measured. If a VT was hemodynamically tolerated, entrainment mapping was performed. For PVCs, activation mapping was performed; if PVCs were infrequent or if a targeted VT was not hemodynamically tolerated, pacemapping was used to identify critical sites.

For PVCs, the site of earliest local activation resulting in PVC elimination with radiofrequency ablation was defined as a critical site. For hemodynamically tolerated VTs, a critical site was defined as a site where there was concealed entrainment and where ablation resulted in VT termination. For nontolerated VTs, an isthmus was defined as a site where there was a pacemap that matched the targeted VT. Radiofrequency energy was delivered to achieve an impedance decrease of >10 Ω with a maximal temperature of 45° C at a power of 30 to 50 W.

The DE-CMR images (Fig. 1) were registered into the EAM (Fig. 2, left) that was constructed in

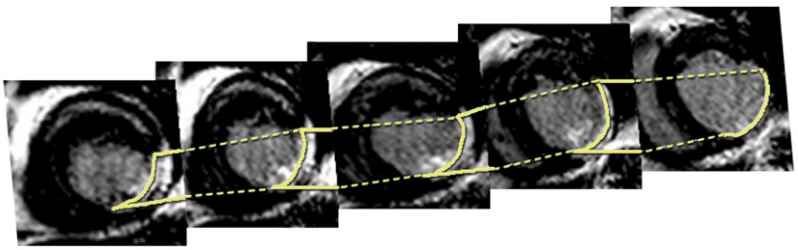

Figure 1. Region of Scar in the Lateral Left Ventricle

Short-axis stack of delayed-enhanced cardiac magnetic resonance images showing a region of scar tissue **(yellow contours)** in the lateral left ventricle.

real time by the following steps using the vendor-integrated segmentation tool of CARTO MERGE: 1) From the DE-CMR images, the endocardial volume was registered as the endocardial shell. 2) Using the same DE-CMR images, the scar area on the DE-CMR images was cut out with the cutting tool function, leaving only the scar behind. An intensity threshold of 2 SDs above the signal of normal myocardium was used to guide the scar segmentation. The scar was then fused with the endocardial shell using a different color (Fig. 2, middle). 3) After the DE-CMR images were rendered, they were registered real time with the EAM (Fig. 2, right). This was achieved with the landmark registration algorithm. In brief, landmark points were identified on the EAM at the aorta, the mitral annulus, and the left ventricular apex. Then the landmark registration process with the corresponding CMR landmarks was performed. As the EAM was completed, registration of EAM data and CMR data was refined with surface registration. Using this approach, a 3-dimensional registration of both image modalities was achieved. The interobserver and intraobserver variability of the cutting process of the DE-CMR–defined scar was determined by the Pearson correlation coefficient. The Pearson correlation coefficient was 0.986 ($p < 0.001$) for the intraobserver and 0.987 ($p < 0.001$) for the interobserver variability.

To assess the accuracy of scar location versus location of low-voltage points in a given area of the voltage map, the percentage of points in the low-voltage areas of the EAM projecting on the scar was determined. The area of the subendocardial scar was measured after it was registered with the EAM using the CARTO XP software. Only the left ventricular endocardium excluding the papillary muscles was used in the registration process.

The positional error using surface registration was 3.8 ± 0.8 mm. The registration process took a mean of 26 ± 5 min. The subendocardial scar area measured by DE-CMR (median, 12.0 cm^2; interquartile range, 6.4 to 41.5 cm^2) correlated with the area of low voltage (<1.0 mV: median, 13.5 cm^2; interquartile range, 7.0 to 30.1 cm^2; $R = 0.82$; $p < 0.001$; <1.5 mV: median, 29.1 cm^2; interquartile range, 13.8 to 62.5 cm^2; $R = 0.62$; $p = 0.003$).

More than 80% of low-voltage points (88 ± 9% when low voltage was defined as <1.0 mV and 86 ± 7% when defined as <1.5 mV) projected on the registered scar. The average bipolar voltage of all low-voltage points that projected onto the registered scar was 0.70 ± 0.18 mV. Twenty-two patients had a single discrete low-voltage area identified on the EAM and a single scar identified by DE-CMR. One patient had 2 low-voltage areas on the EAM and 2 scars on DE-CMR. In all patients, each low-voltage area on the EAM correlated with the scar identified by DE-CMR.

The registration of the DE-CMR–rendered scar and the low-voltage area on the EAM was compared with the registration of the DE-CMR–

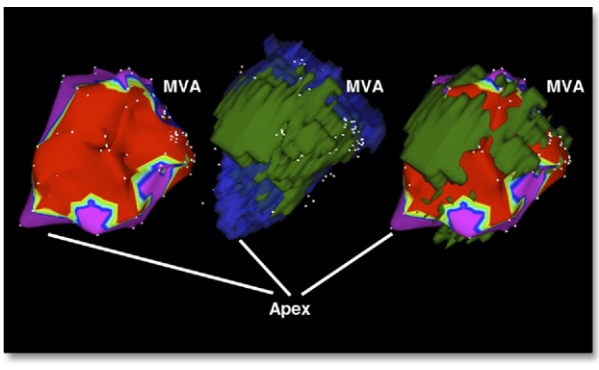

Figure 2. Series of Images of Electroanatomical Map and 3-Dimensional Reconstruction of Scar and Left Ventricular Endocardium

Voltage map with a cutoff voltage of 1.5 mV **(left)**. Merged endocardial cardiac magnetic resonance image shell **(blue)** with scar shell **(green)** **(middle)**. Merged cardiac magnetic resonance image of scar **(green)** with electroanatomical map **(right)**. MVA = mitral valve annulus.

rendered left ventricle and the left ventricular EAM. This demonstrated that 92.4% of the low-voltage points were within 5 mm of the DE-CMR–defined scar and 92.2% of the points of the entire EAM were within 5 mm of the DE-CMR–rendered left ventricular endocardial shell.

Ablation. In the 13 patients with PVCs, the site of origin was identified and effectively ablated in all patients. In patients with VT, a critical isthmus was identified for 19 VTs. All critical sites for PVCs and for VTs were confined to the registered DE-CMR–based scar.

Follow-up. The patients in this study were followed for an average of 49 months (range 15 to 74 months). Amiodarone was continued in 1 patient in whom all VTs were not ablated. In 1 patient, treatment with amiodarone was initiated for atrial fibrillation. One patient had recurrent VT and was treated with sotalol. In patients with frequent PVCs, the PVC burden was reduced from 20.2 ± 15.3% to 0.57 ± 0.94%, representing a decrease of 96% ($p = 0.001$). One of the patients had a recurrence of the ablated PVCs. The ejection fraction increased from 47 ± 11% before ablation to 54 ± 10% post-ablation in patients in whom PVCs were targeted ($p = 0.078$) and remained unchanged in patients in whom VTs were targeted (43.7 ± 18 vs. 41.5 ± 14; $p = 0.98$).

The results of our initial study demonstrate that identification and registration of post-infarction scar tissue with EAMs can be accomplished in real time with the segmentation tool that is integrated into the CARTO XP software. Because post-infarction arrhythmias originate from scar tissue, this approach may facilitate the mapping process by identifying the areas of scar tissue. This study confirms the results of previous studies in which different imaging modalities were used to identify scar tissue in post-infarction patients (3,4). The present study is the first study in which previously acquired DE-CMR data were registered in real time during an ablation procedure. Integration of a scar image into the mapping system allows the mapping process to focus on a particular area. Registration of CMR data with EAM data was accomplished in previous studies (4,5). However, these registrations were performed post hoc without direct benefit to the patient in whom the CMR was performed. In the present study, registration of the exported scar was helpful with the mapping and ablation procedure in that it allowed the mapping process to be focused on a particular area.

A previous study used customized software that is not available to others (5). In contrast, we demonstrate in this study that the vendor-supplied integrated segmentation tool can be used to identify and selectively extract the 3-dimensional structure of the scar that is displayed in the DE-CMR images. Both short- and long-axis images can be used for this purpose. The scar selection and extraction process can be performed with minimal training and minimal time and with accuracy.

The main limitation of the pilot study is the absence of a control group. The study demonstrates the feasibility of real-time registration of electroanatomical data with the scar from a previously obtained CMR image. A randomized study will need to be conducted to show that efficacy or efficiency is improved by scar registration.

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Key Words: ablation ■ cardiac magnetic resonance ■ mapping ■ post-infarction ■ ventricular arrhythmias.