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Original Article

# Scar characteristics derived from two- and three-dimensional reconstructions of cardiac contrast-enhanced magnetic resonance images: Relationship to ventricular tachycardia inducibility and ablation success

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ABSTRACT

*Background:* The relationship between cardiac contrast-enhanced magnetic resonance imaging (CE-MRI)-derived scar characteristics and substrate for ventricular tachycardia (VT) in patients with structural heart disease (SHD) has not been fully investigated.

*Methods:* This study included 51 patients (mean age, 63.3 ± 15.1 years) who underwent CE-MRI with SHD and VT induction testing before ablation. Late gadolinium-enhanced (LGE) regions on MRI slices were quantified by thresholding techniques. Signal intensities (SIs) 2–6 SDs above the mean SI of the remote left ventricular (LV) myocardium were considered as scar border zones, and SI > 6 SDs, as scar zone, and the scar characteristics related to VT inducibility and successful ablation via endocardial approaches were evaluated.

*Results:* The proportion of the total CE-MRI-derived scar border zone in the inducible VT group was significantly greater than that in the non-inducible VT group (26.3 ± 9.9% vs. 19.2 ± 7.8%, respectively, $P=0.0323$). The LV endocardial scar zone to total LV myocardial scar zone ratio in patients whose ablation was successful was significantly greater than that in those whose ablation was unsuccessful (0.61 ± 0.11 vs. 0.48 ± 0.12, respectively, $P=0.0042$). Most successful ablation sites were located adjacent to CE-MRI-derived scar border zones.

*Conclusions:* By CE-MRI, we were able to characterize not only the scar, but also its location and heterogeneity, and those features seemed to be related to VT inducibility and successful ablation from an endocardial site.



## 1. Introduction

Ventricular tachycardia (VT) occurring in the presence of structural heart disease (SHD) can be fatal. The main mechanism of VT is reentry, and the circuits exist mainly in or adjacent to scar border zones. The critical isthmus of the VT circuit is often located within the scar or scar border zones, and such isthmus can be identified in three-dimensional (3D) electroanatomic maps created during entrainment mapping of VT and upon mapping delayed or fragmented potentials and/or pace mapping performed during the sinus rhythm [1,2]. The critical isthmus of the VT circuit has been used as the target for ablation. However, VT ablation remains challenging, particularly in patients with nonischemic cardiomyopathy or arrhythmogenic right ventricular cardiomyopathy (ARVC) because epicardial ablation is often required to eliminate critical VT circuits [3]. Therefore, determining whether VT can be ablated from the left ventricular (LV) endocardium before the procedure in patients with SHD is clinically important. Cardiac contrast-enhanced magnetic resonance imaging (CE-MRI) with late gadolinium enhancement (LGE) is a robust tool for detecting fibrosis in patients with SHD [4–10]. Scar distribution and heterogeneity can also be identified by CE-MRI [4,11,12]. Heterogeneous scar tissue results in slow conduction and becomes the substrate for reentrant VT [10]. We, therefore, conducted a study to examine the relationship between the scar characteristics revealed by CE-MRI and VT inducibility, and the ablation outcomes.

## 2. Materials and methods

### 2.1. Study population

The study group comprised 51 consecutive patients (42 men, 9 women; mean age, 63.3 ± 15.1 years) with SHD and VT who underwent electrophysiologic study and CE-MRI before ablation therapy between September 2007 and May 2015. In all 51 patients,

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the VTs were documented by ambulatory electrocardiography (ECG), 12-lead ECGs, or 24-h Holter ECG monitoring. The patients' SHD resulted from remote myocardial infarctions ($n=20$), cardiac sarcoidosis ($n=12$), hypertrophic cardiomyopathy ($n=10$), ARVC ($n=3$), dilated cardiomyopathy ($n=4$), or cardiomyopathy of unknown etiology ($n=2$). Patients for whom CE-MRI was contraindicated, including those with pacemakers or defibrillators, those with stage IV/V chronic kidney disease, or those unable to lie flat, were excluded. The study protocol was approved by our institutional review board, and all patients provided written informed consent for their participation.

### 2.2. ECG criteria for the QRS fragmentation

The RSR′ pattern included various QRS interval morphologies (QRS duration $<120$ ms) with or without Q waves. Fragmentation inside the QRS was defined by the presence of an additional R wave (R′) or notching in the nadir of the S wave or the presence of $>1$ R′ (fragmentation) in two contiguous leads. A typical bundle-branch block pattern (QRS $>120$ ms) and incomplete right bundle-branch block were excluded from the study [13].

### 2.3. CE-MRI protocol

All CE-MRI were obtained with a 1.5-T MR scanner (Achieva, Philips Medical Systems, Best, The Netherlands) using five-channel SENSE cardiac coils. Scout images were acquired initially to determine the cardiac axes. ECG-gated breath-hold steady- state free precession cine images were obtained in two-, three-, and four-chamber views, and in 2.5-mm short-axis slices from the base to the apex. A gadolinium-based contrast agent (0.2 mmol/kg, Gadovist, Schering, Berlin, Germany) was administered intravenously, and a breath-hold segmented inversion recovery gradient echo sequence was obtained 10 min after the contrast injection and in the same orientation as the cine images [4–12]. The slices were matched as closely as possible to those obtained for the cine and LGE sequences.

### 2.4. Image analysis

All CMR images were analyzed by electrocardiologists blinded to the results of the electrophysiologic evaluations. The LV endocardium and epicardium were traced manually on the short-axis slices obtained at end diastole (Ziostation 2 software, Ziosoft, *Tokyo,Japan*). All short-axis slices covering the entire LV were inspected visually to identify the normal myocardium (Fig. 1**A**), which was taken as the region with no contrast enhancement and normal wall thickness. A region of interest (ROI) in the normal area was planimetered, and the mean signal intensity (SI) and standard deviation (SD) of the SI were calculated (Fig. 1**B**, upper panel). Thereafter, any area of hyperenhancement was identified and outlined. A scar zone was defined by a specific SI threshold, i.e., an SI of $>6$ SD of the normal area [5,8,9] and displayed in red, whereas a scar border zone was defined by an SI of $>2$ SD and $\leq 6$ SD of the normal area and displayed in yellow (Fig. 1A, B lower panel) [9,14]. Summing the planimetered areas in all LGE slices yielded the total masses of the scar and scar border zones, and those were expressed as percentages of the total LV myocardium (%scar and %scar border zones) [11,12] (Supplemental file). Two ratios, representing the scar and scar border zones on the endocardial side of the LV, were calculated as follows: scar zone (g) in the LV endocardium/total LV myocardial scar zone (g) and scar border zone in the LV endocardium (g)/total LV myocardial scar border zone (g), respectively (Fig. 1C). The endocardial side of the LV was defined as the LV endocardium, including the LV myocardium up to 50% of its thickness. For the 10 most recently enrolled patients, 3D-reconstructed CE-MR images of the LV were also created with the use of custom software (M.I. Systems, Kobe, Japan) (Supplemental file).

### 2.5. VT induction and catheter ablation

Electrophysiologic studies and ablation were performed under sedation achieved with midazolam and fentanyl. A 6-Fr quadripolar catheter was introduced via the right femoral vein and placed across the tricuspid valve to record His bundle electrograms, and a second 7-Fr quadripolar catheter was introduced similarly and placed in the right ventricular (RV) apex for pacing. VT was induced from the RV apex and outflow tract by delivering single, double, or triple extra stimuli during basic cycle lengths of 400 and 600 ms. The same steps were taken under isoproterenol infusions (0.25 μg/min) if VT was not induced by programmed stimulation. Inducible VT was defined as induction of sustained monomorphic VT that lasted $\geq 30$ s or that requiring cardioversion because of hemodynamic compromise. Mapping was performed in the RV or LV, depending on the morphology of the targeted ventricular arrhythmias. Intravenous heparin was administered to maintain an activated clotting time of $>250$ s and $>200$ s during LV and RV mapping, respectively. Electroanatomical voltage mapping was performed with a 3.5-mm irrigated-tip catheter (1-mm ring electrode, 2-mm interelectrode spacing; NaviStar ThermoCool, Biosense Webster Inc, Diamond Bar, CA, USA) and CARTO system (Biosense Webster Inc., Diamond Bar, CA, USA). Intracardiac electrograms were filtered at 30–500 Hz (bipolar) and 1–250 Hz (unipolar). In cases of hemodynamically stable VT, potential re-entry circuit sites targeted for ablation were identified based on activation and entrainment mapping. The potential ablation sites were identified by substrate and pace mapping for unstable VTs. Low voltages were defined as bipolar voltage amplitudes of $<1.5$ mV, with scar defined as $<0.5$ mV and scar borders as 0.5–1.5 mV. Fractionated and delayed potentials were mapped from the LV endocardium at bipolar voltages of $<1.5$ mV. For analysis purposes, RF ablation target sites were defined as sites with (1) good pace maps, i.e., matching surface morphologies in 11/12 electrogram leads, or (2) a critical isthmus identified by concealed entrainment and a post-pacing interval equal to the VT cycle length, or (3) VT termination during ablation. Radiofrequency power output was initially set at 30 W and increased up to 40 W. Ablation was performed during VT in patients with hemodynamically stable VT and during sinus rhythm in patients with hemodynamically unstable VT to target all fractionated and/or delayed potentials. Programmed stimulation was repeated after ablation, and successful catheter ablation was defined as non-inducibility of sustained monomorphic VT.

### 2.6. Statistical analysis

Continuous variables were expressed as the mean $\pm$ SD. Between-group differences in continuous variables, including clinical, electrocardiographic, and echocardiographic variables, were analyzed by an unpaired $t$ test or Mann–Whitney $U$ test, as appropriate. Categorical variables are expressed as percentages, and between-group differences were analyzed by a Fisher exact test. All statistical analyses were performed with JMP 9 software (SAS Institute, Cary, NC, USA), and $P<0.05$ was considered statistically significant.

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