Feasibility of image-based simulation to estimate ablation target in human ventricular arrhythmia

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BACKGROUND Previous studies suggest that magnetic resonance imaging with late gadolinium enhancement (LGE) may identify slowly conducting tissues in scar-related ventricular tachycardia (VT).

OBJECTIVE To test the feasibility of image-based simulation based on LGE to estimate ablation targets in VT.

METHODS We conducted a retrospective study in 13 patients who had preablation magnetic resonance imaging for scar-related VT ablation. We used image-based simulation to induce VT and estimate target regions according to the simulated VT circuit. The estimated target regions were coregistered with the LGE scar map and the ablation sites from the electroanatomical map in the standard ablation approach.

RESULTS In image-based simulation, VT was inducible in 12 (92.3%) patients. All VTs showed macroreentrant propagation patterns, and the narrowest width of estimated target region that an ablation line should span to prevent VT recurrence was 5.0 ± 3.4 mm. Of 11 patients who underwent ablation, the results of image-based simulation and the standard approach were consistent in 9 (82%) patients, where ablation within the estimated target region was associated with acute success (n = 8) and ablation outside the estimated target region was associated with failure (n = 1). In 1 (9%) case, the results of image-based simulation and the standard approach were inconsistent, where ablation outside the estimated target region was associated with acute success.

CONCLUSIONS The image-based simulation can be used to estimate potential ablation targets of scar-related VT. The image-based simulation may be a powerful noninvasive tool for preprocedural planning of ablation procedures to potentially reduce the procedure time and complication rates.

KEYWORDS Image-based simulation; Ventricular arrhythmia; Catheter ablation; Cardiac MRI; Computer simulation

ABBREVIATIONS 3-D = 3-dimensional; **ECG** = electrocardiogram/electrocardiographic; **EPS** = electrophysiology study; **HZ** = heterogeneous zone; **ICD** = implantable cardioverter-defibrillator; **LGE** = late gadolinium enhancement; **LV** = left ventricular; **MI** = myocardial infarction; **MRI** = magnetic resonance imaging; **SI** = signal intensity; **VT** = ventricular tachycardia

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Introduction

Scar-related ventricular tachycardia (VT) most commonly results from healed myocardial infarction (MI) and is frequently refractory to medical therapy. Perpetuation of VT critically depends on the regions of relatively slow conduction of the impulse that allows other segments of the heart to recover excitability.[1,2] The current approach of therapeutic ablation is to use invasive catheters to "search and destroy" this slowly conducting tissue. However, this approach is time-consuming and often inaccurate, because VT cannot always be inducible during electrophysiology study (EPS) and it may be hemodynamically unstable. These limitations result in long procedure time, high complications rates, and high recurrence rates.[3–5]

Previous studies suggest that magnetic resonance imaging (MRI) with late gadolinium enhancement (LGE) may identify these slowly conducting tissues. The *heterogeneous zone* (HZ), defined as a highly complex mixture of scar and normal-appearing tissue in transition between the scar and the preserved

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normal tissues, is a structural basis of slowly conducting tissue.[1,6] The HZ is commonly found in the infarct border zone. We have previously demonstrated that (1) MRI with LGE can identify the HZ, (2) the LGE-derived HZ contains regions of abnormal electrical conduction, represented by fractionated electrograms, which are standard targets for ablation, (3) the HZ can be found in the pathway within the VT circuit, and (4) successful VT ablation targets are localized within the HZ, and incomplete ablation of the HZ is associated with recurrence.[7–9] Others also found that the LGE-derived HZ volume is a clinical predictor of VT and death.[10–12]

On the basis of these results, we hypothesized that the HZ identified noninvasively by LGE contains the slowly conducting tissue that is the critical part of the VT circuits. To identify the critical components of the HZ that participate in the VT circuits, we can use a patient-specific, image-based computational simulation. We conducted a retrospective study to evaluate the feasibility of image-based simulation to estimate the potential ablation targets in scar-related VT.

Methods

The study workflow is shown in Figure 1. This study was retrospective but was conducted in a double-blind fashion, where the procedure operators were blinded to the simulation results and those who performed image processing and simulation were blinded to the clinical results. Please refer to the Online Supplement Material for detailed methods.

Study population

We retrospectively evaluated the patients who were referred for catheter ablation of VT between July 2006 and April 2011. Patients were included if preablation MRI with LGE showed myocardial scar, and patients were excluded if preablation MRI showed any artifacts within the heart from an implantable cardioverter-defibrillator (ICD) and/or the ICD leads. The patients underwent cardiac MRI with LGE with a 1.5-T scanner (Avanto, Siemens Medical Solutions, Erlangen, Germany).[10]

EPS and ablation

All the patients underwent the standard EPS and ablation of scar-related VT under the guidance of a 3-dimensional (3-D) electroanatomical mapping system (CARTO, Biosense Webster, Diamond Bar, CA). The standard substrate modification with radiofrequency ablation was performed during sinus rhythm. After ablation, programmed stimulation was repeated. Acute success was defined as the inability to induce clinical VT at the end of the procedure. If nonclinical VT morphologies were inducible, those were also ablated.

Image processing

A finite element mesh of the heart was created from the LGE images for computer simulation. The *scar* was defined as the myocardium with signal intensity (SI) greater than 50% of the maximal SI within the myocardium, and the *HZ* was defined as the myocardium with SI greater than the peak SI in the remote normal myocardium but less than 50% of the maximal SI within the myocardium.[10] Myofiber orientation in the ventricles was estimated on the basis of a modification of a rule-based method[13] where the transmural myofiber direction was assigned as a linear function of the distance from the endocardium to the epicardium, from $+60^\circ$ to -60°, respectively, with reference to the circumferential direction (Figure 1).[14] The transmural myolaminar sheet direction was fixed at -30° with reference to the radial direction.[15]

Computer simulation

We used a biophysically detailed model of whole heart electrophysiology to simulate VT. Ventricular tissue was modeled as monodomain, and the passive tissue properties anisotropic. The scar was modeled as an insulator. Membrane kinetics of the noninfarct tissue was represented by the ten

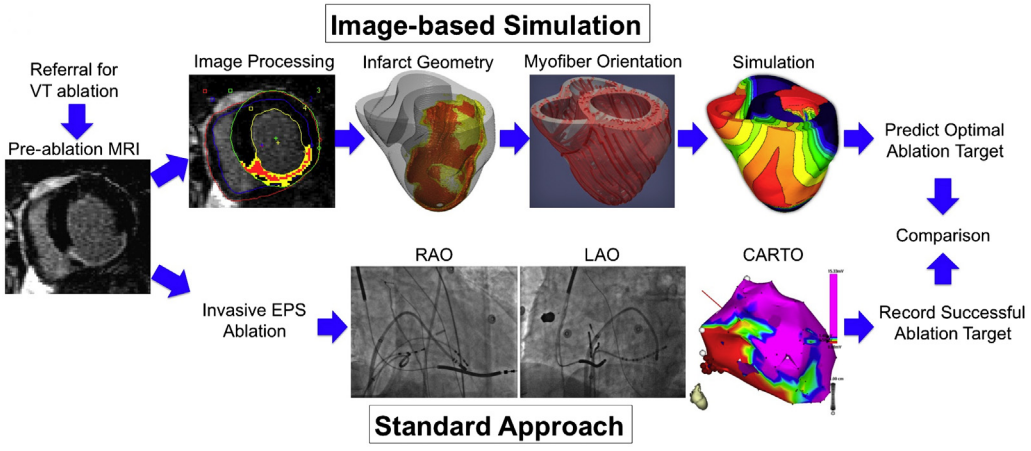

Figure 1 Study workflow. The patients referred for ventricular tachycardia (VT) ablation (n = 13) underwent preablation magnetic resonance imaging (MRI), which was processed to provide the heart and infarct geometry (scar: red; HZ: yellow) and estimated myofiber orientation ("Image-Based Simulation"). These geometrical data were incorporated into mathematical simulation of VT to estimate potential target regions. Patients underwent an invasive electrophysiology study (EPS; n = 13) and ablation ("Standard Approach"; n = 11) by using biplane X-ray fluoroscopy and 3-dimensional (3-D) electroanatomical mapping (CARTO). Ablation lesion locations were recorded in 3-D space and were compared with the target regions estimated by simulation. The study was retrospective but was conducted in a double-blind fashion, where the procedure operator was blinded to the simulation results, and the person who performed image processing and simulation was blinded to the clinical results. LAO = left anterior oblique; RAO = right anterior oblique.