The critical isthmus sites of ischemic ventricular tachycardia are in zones of tissue heterogeneity, visualized by magnetic resonance imaging

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BACKGROUND A need exists to devolop alternative approaches to VT ablation that provide an improved delineation of the arrhythmogenic substrate.

OBJECTIVE The aim of this study was to evaluate the hypotheses that: (1) the heterogeneous zone (HZ, a mixture of normal-appearing tissue and scar) in magnetic resonance imaging (MRI) contains the critical isthmus(es) for ventricular tachycardia (VT), (2) successful ablation of VT would include ablation in the HZ, and (3) inadequate ablation of HZ allows for VT recurrence.

METHODS MRI and an electrophysiology study (EP) were performed in a model of chronic myocardial infarction in 17 pigs. In animals that were inducible for VT, ablations were done guided by standard EP criteria and blinded to the MRI. After ablation, electroanatomic mapping results were co-registered with MRI.

RESULTS In 8 animals, 22 sustained monomorphic VTs were generated. The HZ was substantially larger in inducible (n = 8) compared with noninducible animals (n = 9) [25% ± 10% vs 13% ± 5% of total scar, respectively, $P = .007$]. Acutely, all targeted VTs were successfully ablated, and postprocedure analysis showed that at least 1 ablation was in the HZ in each animal. In 5 animals, a second EP and MRI were performed 1 week after ablation. Three animals had inducible VTs, and MRI showed that the HZ had not been completely ablated. In contrast, the 2 animals without inducible VT revealed no remaining HZ.

CONCLUSION These findings show that MRI can define an HZ and determine the location of ablated lesions. The HZ may be a promising ablation target to cure ischemic VTs. Remnants of HZ after ablation may be the substrate for clinical relapses.

KEYWORDS Ischemic ventricular tachycardia; Catheter ablation; MRI

ABBREVIATIONS **3D** = three-dimensional; **CT** = computed tomography; **EP** = electrophysiology; **HZ** = heterogeneous zone; **LV** = left ventricular; **MI** = myocardial infarction; **MRI** = magnetic resonance imaging; **RF** = radiofrequency; **VT** = ventricular tachycardia

(Heart Rhythm 2011;8:1942–1949)

Introduction

A number of criteria for mapping and ablation of ventricular tachycardia (VT) after myocardial infarction (MI) have been established.[1–3] In patients in whom isthmuses of viable myocardium can be identified within scar, interruption of such isthmuses can eliminate VT.[4] In a minority of patients, the induction of VT does not cause significant hypotension, and entrainment and activation mapping can be done to identify the critical path of reentry. Success rates have been reported to be approximately 75% after successful mapping procedures.[5] Best results are obtained when there is accurate guidance of the ablation catheter using specific mapping criteria.[1] An intention-to-treat analysis of patients referred for VT ablation in the setting of healed MI yielded 58% initial success and 71% eventual success with >1 procedure.[6] Complications such as perforation and emboli can be as high as 8%, likely due to the sometimes prolonged duration of the procedure,[7] and there can still be a greater than 33% recurrence rate.[3]

In the majority of patients, however, induction of VT leads to severe hypotension, and entrainment and activation mapping during VT is not possible. Voltage mapping during sinus rhythm has been used to identify low-voltage areas (<1.5 mV),[8] which are presumed to be areas of a scar (including its

This work has received funding from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement 219384; National Heart, Lung, and Blood Institute R01 HL64795 and R01 HL94610; and the Donald W. Reynolds Foundation. Presented in part at the American Heart Association Scientific Session 2009 in Orlando, Florida. **Address reprint requests and correspondence:** Dr. Heidi L. Estner, Division of Cardiology, Johns Hopkins University School of Medicine, 720 Rutland Avenue, Traylor 903, Baltimore, MD 20215. E-mail address: heidi@estner.org. (Received February 8, 2011; accepted July 19, 2011.)

  doi:10.1016/j.hrthm.2011.07.027

border zone). Pace mapping can then be used to reproduce the QRS morphology of a previously recorded clinical VT, and thereby identify an isthmus where the VT exits from the scar.[9] Ablation of an identified isthmus of viable tissue between scar islands can eliminate VT, as well as placing a line of ablations aimed at connecting the area of scar with another anatomic barrier, such as the mitral annulus.[10] Current voltage and pace mapping techniques can be difficult, however, because of ambiguities in correlating maps with anatomy, as well as possible missed critical sites due to the point-by-point endocardial sampling nature of current methods. Thus, a need exists to develop alternative approaches to VT ablation that would provide an improved delineation of the arrhythmogenic substrate.

Magnetic resonance imaging (MRI) can visualize scar and viable tissue, as well as ablation lesions. It has been shown in a swine model of MI that multiple VT morphologies can be induced.[11] In this latter study, MRI demonstrated the presence of scar containing isthmuses of viable myocardium, resulting in a heterogeneous zone (HZ), which may be the critical substrate for the multiple VT morphologies.[11]

The purpose of this study was to use conventional late gadolinium enhancement MRI to (1) help determine the relationship between VT inducibility and the extent of the HZ, and (2) define the location of ablation lesions with respect to the HZ. Conventional electrophysiology (EP)-guided ablation, blinded to MRI, was performed to prevent bias. We tested the hypotheses that: (1) the HZ is the critical substrate for VT, (2) successful ablation of VT would include ablation in the HZ, and (3) inadequate ablation of the HZ may allow for recurrence of VT.

Methods

Full experimental details are available in the Online Supplementary Material.[12]

MI preparation

Twenty-five domestic swine were studied with an occlusion of their mid-left anterior descending coronary artery.

Experimental protocol

At least 4 weeks after MI induction, the animals underwent in vivo MRI in a 3.0-T scanner (Achieva, Philips Medical Systems, Best, the Netherlands) for assessment of cardiac function and visualization of the HZ. Additionally, a computed tomography (CT) scan was done for merging the left ventricular (LV) endocardial surface and aorta with a three-dimensional (3D) electroanatomic mapping system (CARTO, Biosense Webster, Inc; Diamond Bar, California). One day after the MRI, an EP study was done to determine inducibility or noninducibility of sustained VT, followed by an ablation procedure in inducible pigs guided by CARTO.

The pigs were allowed to survive the VT ablation procedure for 7 to 9 days. They then underwent (1) an EP study that again tested for inducibility of VT, and (2) an in vivo and ex vivo MRI to visualize the HZ.

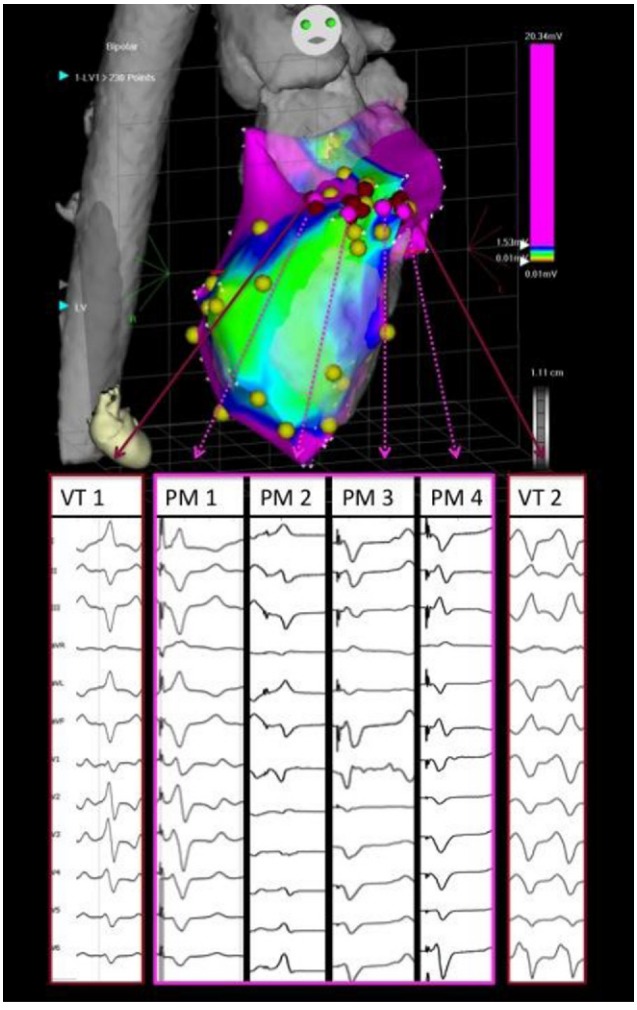

Figure 1 **A:** Electroanatomical voltage map in an animal with a large apicoseptal LV infarction. The voltage maps were constructed from 207 ± 32 points, and the reconstructed colors correspond to voltages on the scale in the upper right corner: purple >1.5 mV, other colors <1.5 mV. Pace mapping (yellow and pink markers) was done around the borders of the identified low-voltage area. **B:** Two of 5 VT morphologies (VT1 and VT2) induced in 1 animal are shown, along with selected pace maps (pink markers corresponding to PM1–PM4). The best pace map for VT1 was PM1, and the best pace map for VT2 was PM4. Other pace maps near the best pace maps were markedly inferior (PM2, PM3). Ablations were done at the locations identified by the best pace maps (red markers), and rendered the corresponding VTs noninducible. Of note, the morphologies of VT 1 and VT2 are markedly different despite having their corresponding best pace maps in close proximity. LV = left ventricular; VT = ventricular tachycardia.

Electrophysiological evaluation and identification of VT circuits

After detailed voltage mapping during sinus rhythm (Fig. 1A), pace mapping was performed in both ventricles. VT exit sites were defined by pace mapping to be sites where the QRS morphology matched the most leads of the 12-lead VT electrocardiogram (Fig. 1B).

Irrigated radiofrequency (RF) energy was delivered at 30 W for 60 seconds. In only 1 animal, a nonirrigated-tip ablation was performed. Ablations were done at the location of the best pace map for each VT morphology. The operators performing the ablations were blinded to the MRI