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Assessment of Radiofrequency Ablation Lesions by CMR Imaging After Ablation of Idiopathic Ventricular Arrhythmias

Karl Ilg, MD,* Timir S. Baman, MD,* Sanjaya K. Gupta, MD,* Scott Swanson, PhD,† Eric Good, DO,* Aman Chugh, MD,* Krit Jongnarangsin, MD,* Frank Pelosi Jr, MD,* Thomas Crawford, MD,* Hakan Oral, MD,* Fred Morady, MD,* Frank Bogun, MD*

Ann Arbor, Michigan

OBJECTIVES To identify and characterize ablation lesions after radiofrequency (RF) catheter ablation of ventricular arrhythmias in patients without prior myocardial infarction and to correlate the ablation lesions with the amount of RF energy delivered and the clinical outcome.

BACKGROUND Visualization of RF energy lesions after ablation of ventricular arrhythmias might help to identify reasons for ablation failure.

METHODS In a consecutive series of 35 patients (19 women, age: 48 $\pm$ 15 years, ejection fraction: 0.56 $\pm$ 0.12) without structural heart disease who were referred for ablation of ventricular arrhythmias, cardiac magnetic resonance imaging with delayed enhancement was performed before and after ablation. Ablation lesions were sought in the post-ablation cardiac magnetic resonance images. The endocardial area, depth, and volume of the lesions were measured. Lesion size was correlated with the type of ablation catheter used and the duration of RF energy delivered.

RESULTS In 25 of 35 patients (71%), ablation lesions were identified by delayed enhancement a mean of 22 $\pm$ 12 months after the initial ablation procedure. The mean lesion volume was 1.4 $\pm$ 1.4 cm^3, with a mean endocardial area of 3.5 $\pm$ 3.0 cm^2. The largest lesions (mean volume of 2.9 $\pm$ 2.1 cm^3 with an endocardial area of 6.4 $\pm$ 3.4 cm^2) were identified in patients in whom the arrhythmias originated in the papillary muscles. Ablation duration correlated with lesion size ($r = 0.67$, $p < 0.001$). There was no difference in lesion volume with irrigated versus nonirrigated ablation catheters (1.0 $\pm$ 0.73 vs. 2.0 $\pm$ 2.1 cm^3, $p = 0.09$). Identification of ablation lesions in patients with a failed procedure identified the sites where ineffective RF energy lesions were created.

CONCLUSIONS RF ablation lesions can be detected long term after an ablation procedure targeting ventricular arrhythmias in patients without previous infarction. Lesion size correlates with the amount of RF energy delivered and is largest when a targeted arrhythmia originates in a papillary muscle. (J Am Coll Cardiol Img 2010;3:278–85) © 2010 by the American College of Cardiology Foundation

From the Departments of *Internal Medicine and †Radiology, University of Michigan Health System, Ann Arbor, Michigan
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Radiofrequency energy applications in ventricular tissue result in localized tissue necrosis and scar formation. Radiofrequency (RF) lesions in the ventricle have been described in animal models (1,2). The purpose of this study was to use cardiac magnetic resonance imaging (CMR) with delayed enhancement to assess the lesions created by RF ablation of idiopathic ventricular tachycardia (VT) and premature ventricular complexes (PVCs).

METHODS

Patient characteristics. Thirty-five consecutive patients (19 women, age: 48 ± 15 years, ejection fraction: 0.56 ± 0.12) without structural heart disease underwent RF ablation of sustained VT (n = 8) or symptomatic, frequent PVCs (n = 27). Nine of 35 patients (26%) had undergone an ablation procedure before referral. All patients underwent CMR before and >1 year after the ablation procedure. All but 2 patients had failed to respond to antiarrhythmic medications, including amiodarone in 2 patients. In 8 of 35 patients, the baseline ejection fraction was abnormal (0.38 ± 0.08) before the ablation procedure because of a reversible cardiomyopathy caused by frequent PVCs (3).

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CMR. CMR was performed with 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 chest of patients in the supine position. Images were acquired with electrocardiogram 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, in-plane spatial resolution: 1.4 × 1.4 mm, slice thickness: 8 mm). Fifteen minutes after administration of 0.20 mmol/kg of intravenous gadolinium diethylenetriaminepentaacetic acid (Magnevist, Berlex Pharmaceuticals, Wayne, New Jersey), 2-dimensional delayed enhancement imaging was performed using an inversion-recovery sequence (4) (repetition time: 6.7 ms, echo time: 3.2 ms, in-plane spatial resolution: 1.4 × 2.2 mm, slice thickness: 8 mm) 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 to null the magnetic resonance signal in the normal left ventricular myocardium. The inversion time was found to be 266 ± 26 ms in patients with left ventricular lesions and 224 ± 24 ms in patients with right ventricular lesions. In the presence of delayed enhancement (Figs. 1 to 3), the lesions were assessed by 2 independent observers. Discrepancies were resolved by consensus. The lesion volume, endocardial lesion area, and maximal lesion depth were measured.

Electrophysiology procedure. The study was approved by the Institutional Review Board of the University of Michigan. After written informed consent, 2 multipolar catheters were inserted into a femoral vein and positioned at the right ventricular apex and the His-bundle location. Programmed ventricular stimulation at 2 right ventricular sites using up to 4 extra stimuli was performed. During the procedure, patients were anticoagulated with an intravenous bolus of 3,000 units of heparin followed by additional doses of 1,000 units per hour for right-sided procedures. For left-sided procedures, an initial bolus of 5,000 units of heparin was given followed by additional dosages to attain an activated clotting time of 250 to 300 s. For mapping and ablation, either a 4- or 8-mm-tip conventional ablation catheter (Navistar, Biosense Webster, Diamond Bar, California) or an open irrigated-tip catheter with a 3.5-mm-tip electrode separated by 1 mm from a 2-mm ring electrode (Thermocool, Biosense Webster) was used in conjunction with a 3-dimensional electroanatomic mapping system (CARTO, Biosense Webster). The intracardiac electrograms and electrocardiographic leads were displayed on an oscilloscope and recorded at a speed of 100 mm/s. All electrograms were filtered at bandpass settings of 50 to 500 Hz. The recordings were stored on optical disc (EP Med Inc., West Berlin, New Jersey).

ABBREVIATIONS AND ACRONYMS

CMR = cardiac magnetic resonance imaging

DE-CMR = delayed enhanced cardiac magnetic resonance imaging

PVC = premature ventricular complexes

RF = radiofrequency

VT = ventricular tachycardia

Mapping and ablation. Activation mapping was performed during VT or PVCs whenever feasible. Pace-mapping was used if PVCs were infrequent or if VT was not reproducibly inducible. Pace-mapping was performed at the cycle length of the targeted VT or at the coupling interval of the targeted PVC (5). A pacing output of 2 to 10 mA was used to achieve capture at a pulse width of 2 ms.

RF energy was delivered at the site of earliest endocardial activation or best pace-map. When a 4-mm-tip catheter was used, RF energy with a 4-mm-tip catheter was delivered in the temperature-controlled mode with a target temperature of 55° to

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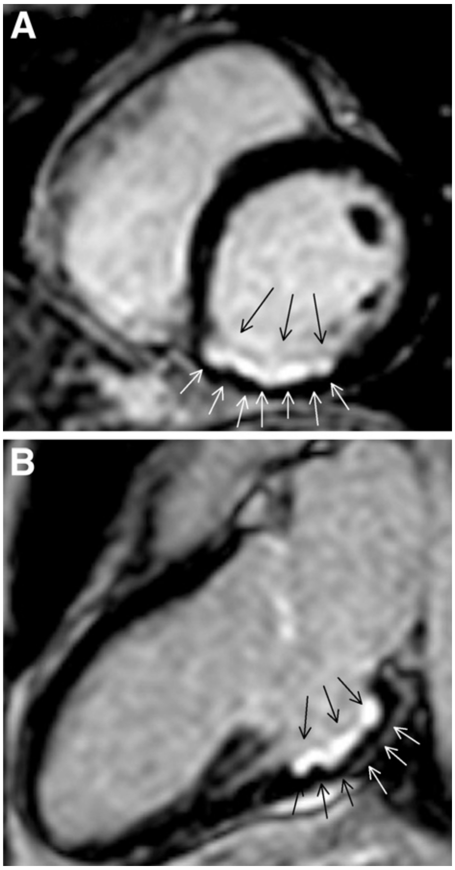

Figure 1. Ablation Lesion After Ablation of a Papillary Muscle Arrhythmia

(A) The short-axis view of a delayed enhanced cardiac magnetic resonance image from a patient in whom premature ventricular complexes originating from the posteromedial papillary muscle were targeted. The enhancing lesion is located posterior to the papillary muscle **(arrows)**. **(B)** A sagittal view through the long axis of the left ventricle illustrating the extent of the enhancing lesion posterior to the papillary muscle **(arrows)**. Ablation was performed with a 4-mm-tip catheter and an 8-mm-tip catheter. The lesion volume measures 1.8 cm^3.

60°C and a power of up to 50 W. If there was inadequate power delivery (<20 W), an 8-mm-tip catheter was used (n = 7). In 21 patients, an irrigated-tip catheter was used for the entire procedure. In patients in whom a transcutaneous epicardial procedure was performed, RF energy was delivered by a 4-mm-tip catheter with a target temperature of 55°C and a power of up to 50 W. Endocardial RF energy delivery with an irrigated-tip catheter was limited to a power of up to 35 W and a maximal temperature of 45°C. After ablation, programmed right ventricular stimulation was repeated. Successful catheter ablation was defined as elimination of ongoing ventricular ectopy or VT by RF ablation, along with the inability to induce PVCs or VT.

Using the cutting function of the CartoMerge software (Biosense Webster), the area of the former ablations were selected and registered and then integrated together with the endocardial shell (Fig. 3) in the electroanatomical map. The lesions were displayed in the active map during the procedure to avoid unnecessary delivery of RF energy at sites that already had been ablated.

For mapping and ablation of arrhythmias originating in a papillary muscle, intracardiac echo was used in 2 of 6 patients. Four of the 6 patients with arrhythmias originating in a papillary muscle had undergone a previous unsuccessful ablation procedure. Intracardiac echocardiography was not used in any of these 4 patients during the initial procedure that resulted in the ablation lesions that were assessed by CMR.

Data analysis. RF energy lesions were assessed in the short-axis, long-axis, and/or sagittal view using OsiriX 3.3.2 software (OsiriX Imaging Software, Geneva, Switzerland). In the delayed enhanced sequences, the lesion depth, endocardial lesion area, and lesion volume were measured. The lesions were correlated with the location of the ablation sites on the electroanatomic maps. The lesion dimensions were correlated with the duration of RF energy delivery, the location of RF energy delivery, the catheter used (irrigated vs. nonirrigated catheter), and efficacy. The volume of the RF energy lesion was correlated with the volume of ventricular muscle. In patients with previous procedures, endocardial low voltage areas (<1.5 mV) were measured and compared with the endocardial lesion size on CMR and the effective ablation site.

Follow-up. All antiarrhythmic drug therapy was discontinued after the ablation procedure. The patients were seen 3 months and 12 to 48 months after the procedure. A 24-h Holter monitor recording and an echocardiogram were performed at 3 to 6 months and the Holter monitor was repeated if palpitations recurred.

Statistics. Continuous variables are expressed as mean ± 1 SD and were compared using a Student *t* test. Discrete variables were compared using the Fisher exact test or by chi-square analysis, as appropriate. If a cell size was <5, Fisher exact test was used. A p value <0.05 was considered statistically significant. A 2-group *t* test was used to compare between pairs of groups where different catheters were used. Bonferroni adjustments to p values were performed for multiple between-pair comparisons. Paired *t* tests were used to compare lesion size from

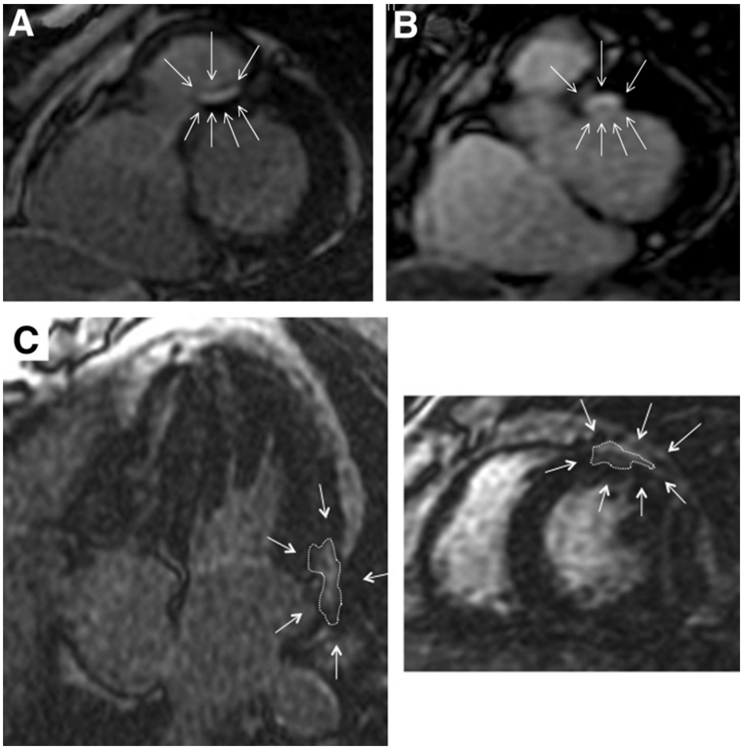

Figure 2. Ablation Lesions at Different Ventricular Locations

(A) Enhancing lesions after ventricular tachycardia originating in the right ventricular outflow tract was targeted **(arrows)**. The lesion was created with an irrigated-tip catheter and is located on the medial aspect of the right ventricular outflow tract; the lesion size measures 0.84 cm^3. **(B)** Enhancing lesions after premature ventricular complexes originating in the left ventricular outflow tract were targeted **(arrows)**. The lesion was created with an irrigated-tip catheter and measures 0.34 cm^3 in volume. **(C)** Enhancing lesions after ablation of ventricular tachycardia originating in the epicardium. Ablation was performed with a 4-mm, nonirrigated-tip catheter. The lesion volume is 0.82 cm^3. The **left panel** shows a long-axis view of the heart and the **right panel** shows a short-axis view. The area with delayed enhancement is encircled with a **dashed line** and indicated by **arrows**.

right versus left ventricle, inversion time in patients with right- versus left-sided lesions and PVC burden before versus after ablation. The continuous variables that were used for parametric comparisons were normally distributed as demonstrated by histograms. Mann-Whitney *U* test was used to compare lesion areas resulting from irrigated versus 4- and 8-mm-tip catheters as the variances were unequal in both groups.

RESULTS

Targeted arrhythmias and ablation. The targeted arrhythmias originated in the right ventricular outflow tract in 17 patients, in the left ventricular outflow tract in 3 patients, in the epicardium in 3 patients, at the mitral annulus in 2 patients, in an aortic cusp in 1 patient, in a papillary muscle in 6 patients, and at other locations (right ventricular apex, right ventricular inflow tract, and anterior fascicle) in 3 patients. Ablation was successful in 29 of 35 patients (83%). In patients with frequent PVCs, the mean PVC burden was reduced from 22 ± 18% to 4 ± 8% ($p < 0.0001$).

Lesion assessment. New sites of delayed enhancement were identified in 25 of 35 patients (71%) by delayed enhanced (DE)-CMR performed a mean of 19 ± 14 months after the ablation procedure. The pre- and post-ablation CMRs were performed a mean of 22 ± 12 months apart. Mean lesion volume was 1.4 ± 1.4 cm^3 with a mean endocardial area of 3.5 ± 3.0 cm^2.

The surface area and the volume of the delayed enhanced lesions correlated with the duration of RF energy delivery (Fig. 4) ($r = 0.67$, $p < 0.001$, and $r = 0.62$, $p = 0.003$, respectively; exclusion of the patient with the longest ablation time would result in $r = 0.71$, $p = 0.001$; exclusion of the patient with the largest ablation lesion would result in $r = 0.6$ and $p = 0.01$). The lesions were larger when the papillary muscles were targeted (mean volume of 2.9 ± 2.1

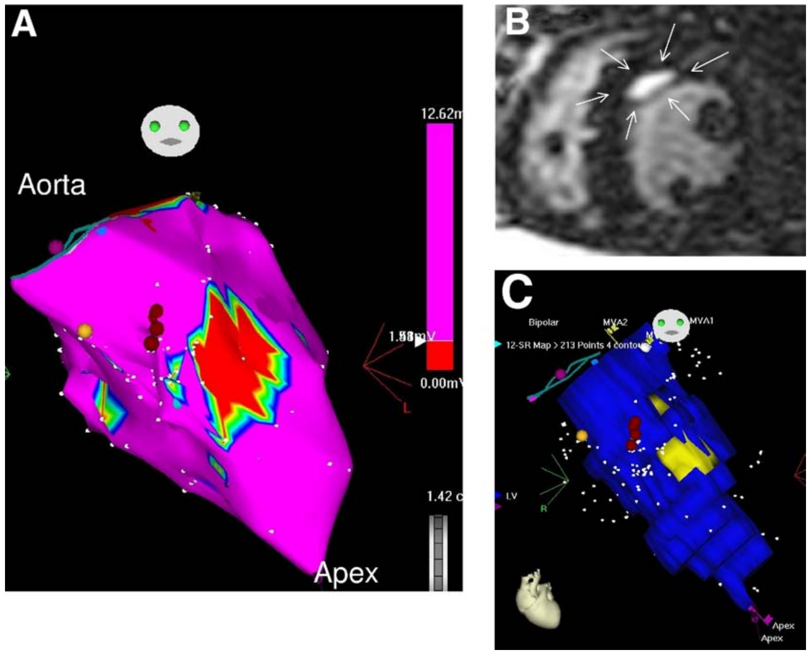

Figure 3. Integration of an Ablation Lesion Into the Electroanatomic Map

(A) Voltage map of the left ventricle in a patient with a previous ablation procedure. The area of low voltage is displayed in **red** and represents sites where previous ablation with an irrigated-tip catheter eliminated frequent premature ventricular complexes originating from the anterior fascicle. The lesion volume was 1.6 cm^3. The **red** tags represent ablation sites, and the **orange** tags indicate the location of the His bundle. The aorta and the left ventricular apex are indicated. The patient had recurrent palpitations due to a premature ventricular complex with a different morphology. **(B)** Cardiac magnetic resonance imaging (CMR) showed a scar **(arrows)** in the anterior septal area from the previous ablation. **(C)** Three-dimensional representation of the left ventricular volume (**blue**) and the scar (**yellow**) based on the delayed enhanced CMR. The scar was imported into the voltage map and matched with the low voltage area. The ablation lesions that resulted in elimination of these premature ventricular complexes are cephalhead of the area of low voltage.

cm^3) than when other sites were targeted (0.9 ± 0.7 cm^3, $p = 0.001$). The lesions were predominantly in the endocardium surrounding the papillary muscle (Figs. 1A and 1B) and <15% of the papillary muscle in which the arrhythmia originated showed delayed enhancement (Table 1).

Ablation lesions were identified in the right ventricle (n = 11) (Fig. 2A), the left ventricle (n = 12) (Fig. 2B), and the epicardium (n = 2) (Fig. 2C). Ablation lesions were similar in volume in the right and the left ventricles (1.4 ± 0.91 cm^3 vs. 1.3 ± 1.7 cm^3, $p = 0.9$). Ablation in the left ventricle resulted in lesions occupying 1.5 ± 1.7% of the left ventricular muscle mass (range 0.2% to 6.5%), and, in the right ventricle, lesions accounted for 2.7 ± 2.0% of the traced right ventricular muscle mass (range 0.5% to 6.7%).

No lesions were seen by DE-CMR in 10 patients in whom arrhythmias in the right ventricular outflow tract (n = 8), the aortic cusp (n = 1), and the epicardium (n = 1) were targeted. No lesions were identified by CMR in 6 of 8 patients in whom RF ablation was performed on the posterior wall of the right ventricular outflow tract, compared with 1 of 11 patients in whom RF ablation was performed at other right ventricular sites ($p < 0.001$). There was not a significant difference in the total duration of RF energy delivery between patients in whom ablation-related scars were and were not seen by DE-CMR (16 ± 10 vs. 10 ± 6 min, $p = 0.13$).

Ablation lesions and catheter technology. Ablation lesion volumes and areas were larger when the combination of a 4- and 8-mm-tip catheter was used than when an irrigated-tip catheter was used, but the difference did not reach statistical significance (Tables 2 and 3). Other comparisons (4-mm-tip vs. 4-/8-mm-tip catheters, 4-mm-tip vs. irrigated-tip catheters) did not show any significant relationships between catheter type and lesion volume, lesion depth, or surface lesion area.

With regard to efficacy, catheter ablation was more often effective with an irrigated-tip catheter than with a 4-mm-tip catheter (95% vs. 43%, $p < 0.05$). There was no difference when irrigated-tip catheters were compared with 4-/8-mm-tip catheters (95% vs. 86%).

No complications occurred during the ablation procedure or during follow-up.

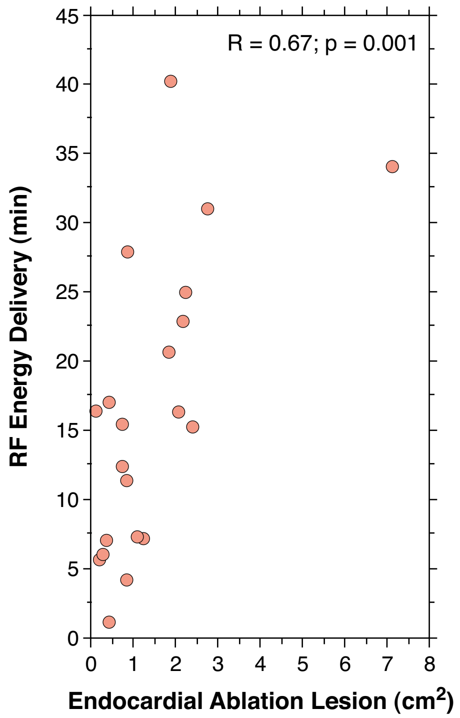

Figure 4. Correlation of Duration of Energy Delivery and Lesion Size

Scattergram showing the correlation between the total duration of radiofrequency energy applications and the area of endocardial delayed enhancement.

Lesion registration in patients with previously failed ablations. In patients with previous procedures, the ablation lesions were registered using CARTO MERGE (Biosense Webster). After landmark and surface registration were performed, the positional error was 3.5 ± 1.6 mm. The area of low voltage measured by electroanatomic voltage mapping was similar in size to the endocardial area of delayed enhancement (5.2 ± 1.9 cm^2 vs. 5.1 ± 0.84 cm^2, $p = 0.9$). In 4 of 9 patients with previously failed ablation procedures, the targeted arrhythmia originated in a papillary muscle; in 3 of 9 patients, there was an epicardial site of origin and an endocardial approach had failed; in 1 patient, the site of origin of a PVC was ablated at the anterior fascicle but the patient had another fascicular focus with a different PVC morphology during follow-up; 1 patient had pleomorphic PVCs resulting in multiple ablation procedures. In 5 of 9 patients, ablation lesions from the previous procedures were found to be adjacent to the effective ablation sites (Fig. 3).

Follow-up. The ejection fraction improved in the 8 patients with an abnormal ejection fraction before ablation from 0.38 ± 0.1 to 0.56 ± 0.12 ($p < 0.0001$).

Table 1. Targeted Arrhythmias and Ablation Lesions

	PAP Arrhythmias (n = 6)	Other Sites (n = 29)	p Value
Procedure time, min	321 ± 85	246 ± 90	0.1
RF ablation time, min	23 ± 15	11.4 ± 7	0.007
Endocardial lesion area, cm^2	6.4 ± 3.4	2.5 ± 2.0	0.003
Lesion volume, cm^3	2.9 ± 2.1	0.9 ± 0.7	0.001
Lesion depth, cm	0.72 ± 0.16	0.49 ± 0.18	0.01
% lesion on PAP	12 ± 10	NA	

NA = not applicable; PAP = papillary muscle; RF = radiofrequency energy.

The mean ejection fraction in all patients improved from 0.56 ± 0.12 to 0.62 ± 0.08. Total follow-up time was 26 ± 13 months. There were no late recurrences after acutely effective ablation procedures.

DISCUSSION

Main findings. This study demonstrates that ablation lesions that target idiopathic ventricular arrhythmias often result in scars that are apparent by DE-CMRs. The lesion size correlates with the duration of RF energy delivery. The largest ablation lesions were observed after ablation of arrhythmias originating in a papillary muscle. These were the arrhythmias that required the most ablation lesions. Irrigated-tip catheters did not result in larger ablation lesions than nonirrigated catheters.

RF energy delivery. DE-CMR has high spatial resolution and can detect even small lesions. As in previous reports (6) of chronic lesions after RF energy ablation in the atrium, ablation lesions in the ventricle were identified by the presence of delayed enhancement.

The major determinants of lesion size were the duration of delivered RF energy and the size of the ablation electrode, with the combination of 4- and 8-mm-tip catheter resulting in the largest ablation lesions. Similar results have been reported in in vivo animal studies (7–9). However the mean lesion volume in this study is larger than the lesion volume

Table 2. Ablation Lesions: Irrigated Versus Nonirrigated Catheters

	Irrigated-Tip Catheter (n = 21)	Nonirrigated Catheter (n = 14)	p Value
Ablation time, min	12.7 ± 10.0	15 ± 9.8	0.5
Ablation lesion area, cm^2	2.7 ± 1.8	4.9 ± 4.1	0.08
Ablation lesion volume, cm^3	1.0 ± 0.73	2.0 ± 2.1	0.09
Maximal lesion depth, cm	0.50 ± 0.21	0.6 ± 0.18	0.12
Effective ablation	20/21 (95%)	9/14 (64%)	0.02

Table 3. Ablation Lesions and Catheters

	Irrigated-Tip Catheter (n = 21)	4-mm-Tip Catheter (n = 7)	4- and 8-mm-Tip Catheter (n = 7)
Ablation time, min	12.7 ± 10.0	13.5 ± 9.8	16.8 ± 10.0
Ablation lesion area, cm^2	2.7 ± 1.8	3.1 ± 2.4	6.7 ± 5.0
Ablation lesion volume, cm^3	1.0 ± 0.73	1.4 ± 1.0	2.8 ± 2.9
Maximal lesion depth, cm	0.50 ± 0.21	0.62 ± 0.2	0.65 ± 0.2
Effective ablation	20/21(95%)*	3/7 (43%)	6/7 (86%)

*$p < 0.05$ versus 4-mm-tip-catheter. Other comparisons between catheter types were not significant with respect to ablation time, lesion depth, lesion area, or lesion volume.

described in animal studies. The largest lesion volume in in vivo animal studies in which ablation lesions were created within a beating heart was <2.0 cm^3 (7,9,10). The mean lesion volume in animal experiments was <1.0 cm^3. The mean lesion volume in the patients in this study was >40% larger.

The larger lesions in this study may be due to a difference in the duration of RF energy applications. However, the amount of ablation performed in this study was similar or less than in other studies in which idiopathic ventricular arrhythmias were ablated (11–15). In some of these reports, the total amount of RF energy delivered was up to 4 times more than in the present study. For example, in 1 report, up to 43 applications of energy were delivered for up to 1 min each (12). Although it is desirable to eliminate idiopathic ventricular arrhythmias with single ablation lesions, this is not always possible, especially when arrhythmias arising in a papillary muscle are targeted.

Anatomic location of ablation. When papillary muscle arrhythmias were targeted, the majority of the ablation lesions were found in the myocardium surrounding the papillary muscle. This indicates that it is difficult to achieve stable contact of an ablation catheter on the papillary muscle. Intracardiac echocardiography may help to decrease unnecessary ablation lesions. In a previous study in which post-infarction VT was targeted, patients in whom more RF energy was delivered had a worse outcome (16). Although in this study ablation lesions predominantly were delivered in the scar border zone or in the scar itself, it is possible that collateral damage was at least in part responsible for adverse outcomes. In patients without structural heart disease, the objective is to limit ablation lesion size and therefore factors contributing to the size of ablation lesions are worthy of investigation.

Irrigated versus nonirrigated catheters. Contrary to previous reports (9,17), irrigated-tip catheters did not result in larger lesion volume than nonirrigated-tip catheters. A possible explanation might be that the power was ≤35 W when an irrigated-tip catheter was used. Nevertheless, compared with 4-mm-tip catheters, the irrigated-tip catheters were more often associated with a successful outcome. The combination of 4- and 8-mm-tip catheters resulted in lesions that were larger than with the irrigated-tip catheter. A possible explanation may be that the precision of mapping is better with a 3.5-mm-tip catheter with 1-mm interelectrode spacing than with an 8-mm-tip with 2-mm interelectrode spacing.

Previous failed ablations. Most of the patients referred for a repeat ablation procedure had arrhythmias originating in a papillary muscle. A scar pattern surrounding a papillary muscle after a failed procedure may indicate that the arrhythmia originated from a papillary muscle. By showing the location of ablation lesions, DE-CMR is helpful in elucidating the reason for ablation failure in these patients. Integration of previous ablation lesions into the real-time ablation procedure helps to identify scars from previous ablation, which helps to limit unnecessary ablation lesions. Identification of low voltage sites might convey the misleading suggestion that scar tissue harboring the arrhythmogenic substrate is present. This might further encourage mapping and ablation in this area. Clarification that previous ablation is responsible for low voltage may help to prevent other ablation attempts in these regions.

Study limitations. A limitation of this report is the small sample size. A larger patient population is required to allow confirmation of the initial observations described in this study with regard to the lesion sizes created by different types of ablation catheters.

Nulling was performed based on the magnetic resonance signal of the normal left ventricular myocardium. Inversion times have been reported to be lower for the right ventricle (18), which might have resulted in under-reporting of right ventricular ablation lesions. This may explain why no ablation lesions were identified in approximately 40% of patients who had undergone ablation in the right ventricle.

Reprint requests and correspondence: Dr. Frank Bogun, Assistant Professor of Medicine, Division of Cardiology, CVC Cardiovascular Medicine, 1500 East Medical Center Drive, SPC 5853, Ann Arbor, Michigan 48109-5853. *E-mail: fbogun@med.umich.edu.*

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Key Words: ventricular arrhythmias ■ cardiac magnetic resonance imaging ■ radiofrequency ablation.