MRI-Guided Ventricular Tachycardia Ablation
Integration of Late Gadolinium-Enhanced 3D Scar in Patients With Implantable Cardioverter-Defibrillators

Timm Dickfeld, MD, PhD; Jing Tian, MD, PhD; Ghada Ahmad, MD; Alejandro Jimenez, MD; Aharon Turgeman, MSc, MBA; Richard Kuk, MD; Matthew Peters, BS; Anastasios Saliaris, MD; Magdi Saba, MD; Stephen Shorofsky, MD, PhD; Jean Jeudy, MD

Background—Substrate-guided ablation of ventricular tachycardia (VT) in patients with implanted cardioverter-defibrillators (ICDs) relies on voltage mapping to define the scar and border zone. An integrated 3D scar reconstruction from late gadolinium enhancement (LGE) MRI could facilitate VT ablations.

Methods and Results—Twenty-two patients with ICD underwent contrast-enhanced cardiac MRI with a specific absorption rate of <2.0 W/kg before VT ablation. Device interrogation demonstrated unchanged ICD parameters immediately before, after, or at 68±21 days follow-up (P>0.05). ICD imaging artifacts were most prominent in the anterior wall and allowed full and partial assessment of LGE in 9±4 and 12±3 of 17 segments, respectively. In 14 patients with LGE, a 3D scar model was reconstructed and successfully registered with the clinical mapping system (accuracy, 3.9±1.8 mm). Using receiver operating characteristic curves, bipolar and unipolar voltages of 1.49 and 4.46 mV correlated best with endocardial MRI scar. Scar visualization allowed the elimination of falsely low voltage recordings (suboptimal catheter contact) in 4.1±1.9% of <1.5-mV mapping points. Display of scar border zone allowed identification of excellent pace mapping sites, with only limited voltage mapping in 64% of patients. Viable endocardium of >2 mm resulted in >1.5-mV voltage recordings despite up to 63% transmural midmyocardial scar successfully ablated with MRI guidance. All successful ablation sites demonstrated LGE (transmurality, 68±26%) and were located within 10 mm of transition zones to 0% to 25% scar in 71%.

Conclusions—Contrast-enhanced cardiac MRI can be safely performed in selected patients with ICDs and allows the integration of detailed 3D scar maps into clinical mapping systems, providing supplementary anatomic guidance to facilitate substrate-guided VT ablations. (Circ Arrhythm Electrophysiol. 2011;4:172-184.)

Key Words: magnetic resonance imaging ■ implantable cardioverter-defibrillators ■ ablation ■ tachycardia ventricular

With expanding implantable cardioverter-defibrillator (ICD) indications, an increasing number of patients present with appropriate ICD shocks for ventricular arrhythmias.1,2 The side effects and lack of long-term efficacy of antiarrhythmics have made ventricular tachycardia (VT) ablation an increasingly attractive treatment option.3,4

Clinical Perspective on p 184

In ∼70% to 90% of patients, a substrate-guided VT ablation must be pursued because of hemodynamic instability or multiple VT morphologies.5,6 During the ablation, tangential or radial lesions are placed along and transecting the scar border in an attempt to eliminate conducting channels and VT exit sites. In these procedures, voltage mapping is the “gold standard” for defining myocardial scar border zone or surviving myocardial channels. However, voltage mapping has multiple limitations: a single endocardial (or epicardial) voltage measurement representing a poor surrogate for a complex intramural 3D scar anatomy, limited spatial resolution of the electroanatomic maps, prolonged mapping times, and falsely low voltage measurements due to imperfect catheter contact.6

MRI is used to accurately delineate myocardial scar,7 but ICDs are present in the majority of patients with VT and are still considered a contraindication or affect imaging quality.8 This study evaluated the safety and diagnostic yield of cardiac MRI (CMR) in the largest reported ICD patient cohort to date, and is the first to assess the feasibility of registered 3D MRI scar reconstructions to facilitate VT ablations in patients with ICDs.

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From the Division of Cardiology (T.D., J.T., G.A., A.J., R.K., M.P., A.S., S.S.) and Radiology (J.J.), University of Maryland, Baltimore, MD; St. George’s Hospital and University of London (M.S.), London, UK; and Biosense Webster Inc (A.T.), Tirat Carmel, Israel.
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Correspondence to Timm Dickfeld, MD, PhD, Division of Cardiology, University of Maryland, 22 S Greene St, Room N3W77, Baltimore, MD 21201. E-mail tdickfel@medicine.umaryland.edu
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172
Methods

Patient Population

Consecutive patients with an ischemic or nonischemic cardiomyopathy and ICD scheduled for VT ablation for frequent ICD therapies were enrolled. Exclusion criteria consisted of device implantation <6 weeks, epicardial lead/coil system, abandoned or capped endo-
vascular leads, ICDs manufactured before 2002, and creatinine clearance <30 mL/min. Written consent was obtained from all
patients after institutional approval of the research protocol.

Pre- and Post-MRI ICD Interrogation

ICD interrogations were performed immediately before and after the MRI
as well as during follow-up visits. During the MRI, tachyarrhythmia
detection and therapy was disabled. In patients dependent on pacemak-
ers, bradycardia parameters were programmed to VOO/DOO mode (60
beats/min). In patients not dependent on pacemakers, the rate-
responsiveness feature was temporarily disabled, and VVI or DDD
programming was left unchanged.

ECG, blood pressure, and pulse oximetry was continuously
monitored during MRI, and clinical symptoms were recorded.
Post-MRI, programming was restored to its original parameters.

MRI

MRI was performed supine using a 1.5-T scanner (Siemens Avanto).
Imaging sequences resulted in a specific absorption rate (SAR) <2.0
W/kg. Cine turboflash sequences, which assess anatomic and dy-
namic characteristics, were performed to assess wall thinning and
contractility (field of view, 320 to 400 mm; repetition time [TR], 75
to 80 ms; echo time [TE], 3 to 4 ms; flip angle, 15°; slice thickness, 8
mm/10 mm spacing). First-pass perfusion using dynamic gradient
echo sequences to assess regional hypoperfusion characteristics were
performed (field of view, 320 to 400 mm; TR, 160 to 165 ms; TE, 1
to 1.5 ms; flip angle, 15°; slice thickness, 8 mm/10 mm spacing).

Inversion recovery images were obtained ECG gated during
diastole 10 to 15 minutes after intravenous injection of 0.1 mg/kg
gadobenate dimeglumine. Short- and long-axis 2D (slice thickness, 8
mm; no gap; inversion time, 250 to 350 ms; TR, 725 to 950 ms;
TE, 1 to 4 ms; flip angle, 25°) and 3D (slice thickness, 4 to 6 mm;
no gap; TR, 700 to 750 ms; TE, 1 to 1.5 ms; flip angle, 10°) inversion
recovery sequences (Figure 1) were obtained after optimal nulling of
the inversion time to assess LGE.

Delineation of MRI-Derived 3D Myocardium and
Left Ventricular Scar

Two-dimensional and 3D MRI scans were exported in DICOM
format to an external imaging workstation. Left ventricular (LV) and
right ventricular (RV) endocardial and epicardial surfaces as well as
intramyocardial boundaries of myocardial LGE were determined by
a radiologist-expert reader with >10 years of experience and hand
planimetered on contiguous, reformatted 2D and 3D slices using
modified Siemens video projection tools and Amira software. In
areas of ICD artifact, an approximated reconstruction of the LV
endocardium and epicardium (without scar) was performed to
facilitate image registration. Scar only was reconstructed from LGE
images and if no significant ICD artifact was present. Reconstructed
3D models of the RV and LV anatomy with embedded myocardial
scar were exported as 3D Carto-readable Mesh files and allowed the
identification of mapping point positions on the corresponding 2D
MRI images. Quantitative and regional scar assessment was per-
formed with Segment version 1.x software.9 Using the image
platform extension research software module (Biosense Webster),
MRI surfaces were uploaded into the clinical CartoMERGE system.

Registration of Voltage Map and MRI-Derived LV
Anatomy and Scar

If the CartoSOUND module was used, an anatomic 3D reconstruc-
tion of the RV and LV was created from sequential 2D intracardiac
ultrasound slices (SoundStar; Biosense Webster) acquired from an
RV position. With a 3.5-mm open irrigation-tip catheter (Thermo-

Cool; Biosense Webster), LV voltage maps were created through a
retrograde or transeptal approach using a filling threshold of 15 mm
and voltage settings of 0.5 to 1.5 mV. Unipolar and bipolar signals
were filtered at 10 to 400 Hz and were acquired during sinus rhythm
or ventricular pacing in case of resynchronization therapy and
pacemaker dependency. Signals were defined as normal potential,
fractionated potential (FP), or diastolic potential (DP).10

Applying an early registration strategy visual alignment of the 3D
MRI reconstruction was performed with the CartoMERGE software
using >10 RV and >50 LV mapping points. Alternatively, using a
CartoSOUND registration approach, the MRI LV and scar reconstruc-
tions were registered to the anatomic 3D RV and LV ultrasound shells,
allowing the display of the extracted LV scar during an early stage of
the LV mapping (early registration) or even before entering the arterial
circulation (CartoSOUND registration). Final registration of the 3D
MRI scar map was performed after completing RV and LV mapping.

For visual alignment, superior mitral valve points (12 o’clock) were
used as determined by electric signals and fluoroscopy with or without
ultrasound. Rotational errors were minimized by aligning the superior
and inferior RV septal insertion sites of the MRI-derived shell with the
RV/LV voltage map (Figure 1). For landmark point registration, LV
apex, mitral valve, and RV septal insertions were selected. Registration
accuracy was determined using the internal CARTO summa-
tics, averaging the distance of the individual mapping points to the
closest surface point of the registered MRI shell.11

VT Ablation

After registration, additional MRI-guided mapping was performed at
sites <1.5 mV remote from matching MRI scar to determine falsely
low voltage recordings due to suboptimal catheter contact as well as
in areas of complex MRI border zone geometry. VT was induced by
programmed electrical stimulation (PES) with up to triple extra
stimuli from 2 RV and up to 2 LV sites (drive cycle length, 350, 400,
and 600 ms; minimum coupling interval, 200 ms). If VT was
nonsustained or not tolerated, pace mapping sites were chosen based
on MRI-defined border zone (after early and CartoSOUND registra-
tion) and the 12-lead VT morphology. Matches >11/12 were used to
determine the approximate exit sites. In case of hemodynamically
tolerated VT, standard entrainment criteria were used within areas of
MRI scar.12 Successful ablation lesions (50 W, 60 seconds) were
defined as terminating VT or occurring at site of pace map matches.

Additional tangential and radial ablation lines were created based
on scar anatomy defined by voltage and MRI data. LV mapping was
completed (unless noted otherwise) to assess final registration and
location of FPVs, DPVs, and voltage-defined border zone. PES was
repeated at the end of the VT ablation. Criteria defining ablation
success were the inability to induce the clinical or presumed clinical
VT or sustained monomorphic VT with longer cycle length.3

Statistical Analysis

SPSS for Windows version 16.0 was used to perform the statistical
analysis. Continuous variables are expressed as mean±1 SD, unless
otherwise noted.

Comparisons between pre- and post-MRI measures were con-
ducted using the Wilcoxon signed rank test. The Spearman rank
correlation test was used to assess possible correlations. Differences
were considered significant at a level of P<0.05. Receiver operating
characteristic (ROC) curves were created for unipolar and bipolar
voltage recordings to identify the best cutoff voltage values to predict
endocardial MRI scar. Areas under the curve (AUCs) for each
voltage recording were reported and compared.

Results

Patient Population

Four of the 26 screened patients were excluded because of an
epicardial ICD system (n=1), abandoned endocardial leads
(n=2), or creatinine clearance of <30 mL/min (n=1). Twenty-two patients were enrolled in the study. Baseline
characteristics are shown in Table 1.
Safety of CMR in Selected Patients With ICDs

Contrast-enhanced CMR (CE-CMR) was performed in 22 patients with single (n=9), dual (n=10), and biventricular (n=3) ICDs (online-only Data Supplement 1). ICDs were interrogated before and after MRI and at 68±21 days follow-up (Table 2). Five devices were equipped with wireless telemetry. Two patients were pacemaker dependent, with ventricular escape rates of <30 beats/min. No significant changes in battery voltage and impedance, atrial or ventricular thresholds, and intrinsic amplitudes or

Figure 1. MRI and extraction of anatomy in patients with ICDs. A, Inverse recovery serial short-axis MRI images (apical-to-base scan plane, 1 to 6). ICD results in high-intensity artifact, affecting the anterior wall. ICD lead seen as low-intensity signal in inferior RV. Transmural LGE seen in inferior wall of LV. B, Registration of extracted 3D MRI. LV voltage map is aligned with MRI-extracted endocardial shell (turquoise). Rotational errors are corrected by aligning RV voltage map with reconstructed MRI RV slice (red). After integration of MRI-extracted epicardial shell (blue mesh), embedded MRI-derived transmural scar (brown) is well visible within the myocardial wall. Endo indicates endocardial; Epi, epicardial.
Impedances were seen among pre-MRI, post-MRI, and follow-up (Table 2).

No complication occurred during the MRI scanning. No inappropriate or inhibited pacing or tachytherapy were observed.

Image Quality of CMR in Patients With ICDs

Anatomic-dynamic and first-pass perfusion magnetic resonance sequences demonstrated limited artifacts and allowed detailed assessment of the septal, inferior, lateral, and anterior wall regarding anatomic-dynamic (100%, 100%, 100%, and 82%, respectively) and perfusion (100%, 100%, 100%, 91%, respectively) characteristics. In LGE sequences for scar visualization, ICD artifacts were more pronounced and appeared as a central signal void (ICD generator) with a visualization, ICD artifacts were more pronounced and assessed in 9±4 segments and partially assessed in 12±3 segments. In patients with ischemia, 82±7% of scar had endocardial components, with midmyocardial or epicardial components being predominately seen as <1-cm scar extensions in the border zone. Of the 7 patients with nonischemic cardiomyopathy, 2 (29%) had exclusively epicardial or midmyocardial scar. Two (29%) patients without ischemia had no identifiable scar.

Extraction and Registration of 3D MRI Scar Map

CE-CMR-based scar integration into a mapping system before ablation was performed in all 14 patients with LGE that proceeded to a VT ablation (ischemic cardiomyopathy, n=11). Of the other 8 patients, 3 underwent placement of an LV assist device or a heart transplant for worsening heart failure, 2 requested to have the MRI stopped because of claustrophobia, 2 had no visible scar, and 1 opted for pharmacological therapy.

Endocardial and epicardial RV and LV borders were successfully hand planimetered on contiguous 2D short-axis slices in all patients with approximated LV wall contours in areas of artifact. Detailed 3D scar anatomy was displayed embedded into the myocardium (Figure 1). LV reconstruction from areas of artifact were separately reconstructed (without scar), with different color annotation to simplify visualization if artifact and scar were adjacent (Figure 2).

Early registration was performed in the first 9 patients using 13±3 RV points and 54±4 LV points with a registration accuracy of 5.7±3.9 mm. In the last 5 patients, MRI-derived LV scar maps were registered to CartoSOUND-reconstructed RV and LV shells, with a registration error of 4.6±3.1 mm.

Final registration accuracy of the completed voltage map (58±39 RV points and 190±32 LV points) was 3.9±1.8 mm using visual alignment and 4.1±2.0 mm with landmark point

Table 1. Baseline Characteristics of Patient Population Undergoing MRI

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>58±15</td>
</tr>
<tr>
<td>Sex, male/female</td>
<td>21/1</td>
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<tr>
<td>Weight, kg</td>
<td>95.1±26.8</td>
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<tr>
<td>Height, cm</td>
<td>177±9</td>
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<tr>
<td>Body surface area, m²</td>
<td>2.1±0.3</td>
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<tr>
<td>VT episodes in previous 30 days</td>
<td>17±12</td>
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<tr>
<td>Ischemic cardiomyopathy</td>
<td>68</td>
</tr>
<tr>
<td>Nonischemic cardiomyopathy</td>
<td>32</td>
</tr>
<tr>
<td>Ejection fraction</td>
<td>34±14</td>
</tr>
<tr>
<td>Hypertension</td>
<td>50</td>
</tr>
<tr>
<td>Diabetes</td>
<td>23</td>
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<tr>
<td>Hyperlipidemia</td>
<td>59</td>
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<tr>
<td>Antiarrhythmic therapy</td>
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<td>Amiodarone</td>
<td>68</td>
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<tr>
<td>Sotalol</td>
<td>28</td>
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<tr>
<td>Quinidine</td>
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</table>

Data are presented as mean±1 SD or %, unless otherwise indicated.

Table 2. ICD Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pre-MRI</th>
<th>Post-MRI</th>
<th>Follow-Up</th>
<th>P (Pre/Post)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-wave amplitude, mV</td>
<td>3.3±2.1</td>
<td>3.0±1.4</td>
<td>3.1±1.6</td>
<td>0.35</td>
</tr>
<tr>
<td>R-wave amplitude, mV</td>
<td>9.9±5.2</td>
<td>10.2±5.4</td>
<td>10.1±5.9</td>
<td>0.09</td>
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<tr>
<td>Atrial lead impedance, Ω</td>
<td>475±78</td>
<td>476±69</td>
<td>462±83</td>
<td>0.51</td>
</tr>
<tr>
<td>Ventricular lead impedance, Ω</td>
<td>461±97</td>
<td>451±89</td>
<td>450±95</td>
<td>0.82</td>
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<tr>
<td>Shock impedance, Ω</td>
<td>45±8</td>
<td>45±8</td>
<td>44±7</td>
<td>0.34</td>
</tr>
<tr>
<td>Atrial capture, V</td>
<td>1.5±0.9</td>
<td>1.4±0.9</td>
<td>1.5±1.0</td>
<td>0.32</td>
</tr>
<tr>
<td>V×ms</td>
<td>0.41±0.23</td>
<td>0.41±0.22</td>
<td>0.41±0.28</td>
<td>0.66</td>
</tr>
<tr>
<td>Ventricular capture, V</td>
<td>1.6±0.7</td>
<td>1.6±0.7</td>
<td>1.5±0.7</td>
<td>0.32</td>
</tr>
<tr>
<td>Battery, V</td>
<td>2.97±0.21</td>
<td>2.97±0.21</td>
<td>2.95±0.22</td>
<td>0.08</td>
</tr>
</tbody>
</table>

ICD parameters measured before and after MRI as well as after 68±21 days of follow-up summarize ventricular leads (n=22) and atrial leads (n=13) measurements. To account for devices allowing only pulse-width decrements, thresholds also are displayed as V×ms. Significance is evaluated with Wilcoxon signed ranks test.
and surface registration (Figure 1B). A full LV map was created in all 9 patients with early registration and 2 out of 5 patients with CartoSOUND registration.

**Intraprocedural MRI Guidance During VT Ablation**

There was a good correlation between myocardial scar defined by CMR and voltage. Endocardial voltage points of <0.1 mV, <0.5 mV, and <1.5 mV demonstrated MRI-defined scar in 100%, 87%, and 75%, respectively. Increasing transmurality of MRI-derived scar correlated with decreasing endocardial bipolar voltage ($r = -0.83$; $P < 0.01$) (Figure 3). ROC curves demonstrated the best cutoff values for bipolar and unipolar voltage recordings to optimally differentiate endocardial scar from nonscar defined by MRI are 1.49 mV (AUC, 0.86 ± 0.01) and 4.46 mV (AUC, 0.78 ± 0.02), respectively.

Procedure time for early registration, CartoSOUND registration, and final registration was 4 ± 3, 5 ± 4, and 5 ± 3 minutes, respectively. The early registration or CartoSOUND registration allowed the visualization of MRI-derived scar size, location, and transmural extent during 71% and 100% of the total LV mapping point acquisition, respectively. Display of the MRI scar guided the further mapping and ablation in several ways.

**Detection of Suboptimal Catheter Contact**

Immediate identification of low-voltage recordings (<1.5 mV) in areas without MRI-derived scar suggested imperfect catheter contact. Repeat mapping using echocardiographic contact confirmation demonstrated that 78 ± 12% of those points (average voltage, 0.83 ± 0.52 mV) were shown to have voltages >1.5 mV, representing 4.1 ± 1.9% of the total original <1.5-mV mapping points. Locations of mislabeled points were midanterior (37%), septal (29%), inferobasal (25%), and lateral (9%).

**Targeted Mapping of Voltage, DP, and FP**

The integration of 3D MRI-defined scar provided an anatomic characterization of the 3D scar and border zone geometry, displaying varying transmurality and epicardial, midcardial, and endocardial scar components (Figure 4). Visualization of complex transition zones of scar transmurality within scar or border zones allowed anatomically targeted mapping for FPs and DPs or preserved voltages. FPs and DPs were found more frequently within 10 mm of the MRI scar border than in the scar center (69 ± 18% versus 31 ± 17%, $P < 0.01$). Additionally, FPs and DPs were found more frequently in areas of >50% versus <50% MRI-defined scar transmurality (68 ± 19% versus 31 ± 18%, $P < 0.01$, and 74 ± 28% versus 26 ± 28%, $P < 0.01$, respectively).
Figure 5. MRI-guided identification of ablation site at scar border. Early registration strategy guided pace mapping (orange-brown tags) along the border of the registered scar mesh and allowed rapid identification of a fractionated, low-voltage site (yellow tag) (A) with
Targeted Pace Mapping, Entrainment, and Ablation
Empirical pace map sites were selected along the displayed MRI border zone guided by the 12-lead VT morphology before completing LV voltage mapping, identifying presumptive VT exit sites with 11/12 pace map match in 64% of patients (Figure 5A and 5B). Pace map matches 11/12 were found within 10 mm of the MRI scar border zone in 77% of VTs. Mapping density generally was 5 to 10 mm in these targeted locations.

MRI detected surviving papillary muscle (PM) within a large area of infarcted myocardium in 7% of patients. Early integration of 3D-reconstructed viable myocardium allowed identification of 11/12 pace map match at the scar-myocardial interface before complete LV mapping (Figure 6).

Despite preserved endocardial voltage (>1.5 mV), the display of MRI midmyocardial scar with a transmurality of 11% to 63% identified a 11/12 pace map match (7% of patients) at the transition zone of enhanced and nonenhanced myocardium (Figure 7). The identification of midmyocardial scar as VT substrate adjacent to alive endocardium at the excellent pace map location suggested a possible endocardial scar exit site, explained the >1.5-mV amplitude, and provided the rationale for ablation in voltage-defined normal myocardium that successfully eliminated the clinical VT.

During bipolar endocardial mapping, a 2-mm rim of viable endocardium was observed in 14% of patients and resulted in >1.5-mV recordings during bipolar endocardial mapping. This result was observed predominantly in patients without ischemia with septal/inferolateral scar location in which the midmyocardial scar accounted for 27% and 100% of total scar, respectively (online-only Data Supplement 2). The preserved voltage would have prevented the detection of adjacent intramyocardial scar based on voltage criteria alone.

Hemodynamically tolerated VT was induced in 14% of patients. Registration of MRI-defined scar to the CartoSOUND shell enabled entrainment mapping within the scar without prior voltage mapping and facilitated the identification of the successful ablation site (Figure 8). In 3 of the 5 patients in whom the CartoSOUND registration strategy was used, real-time visualization of radiofrequency (RF) lesions within the MRI-defined abnormal substrate could be confirmed by increasing local ultrasound signal intensity (Figure 8).

Ablation Results
At PES 2.4±1.2 different VTs per patient were inducible, with at least 1 VT matching the presumed clinical VT by 12-lead surface ECG and ICD-based intracardiac morphology and rate. Cycle length was 389±99 ms with 5 left bundle branch, 24 right bundle branch, and 4 indeterminate morphologies (online-only Data Supplement 2).
Twenty-two VTs were targeted for ablation. Acute procedural success was assessed with PES, including double \( (n=11/10) \) and triple extra stimuli \( (n=8) \). Clinical VT remained inducible \( (n=1) \), or monomorphic VT, which was faster than the clinical VT but had not been previously clinically observed, was inducible and was not ablated \( (n=6) \).

All successful ablation sites demonstrated MRI scar (Figures 5C through 5F and 7E and 7F). Average scar transmurality was \( 68 \pm 26\% \) (30\% to 100\%). Eighty-one percent of ablation sites had \( \geq 50\% \) transmural scar components and were located within 10 mm of transition zones to 0\% to 25\% transmural scar in 71\%. Successful ablation sites were more commonly located in the scar periphery (76\%). Additional linear ablations were created (1) along voltage- and MRI-defined scar borders \( (n=12 \) patients); (2) connecting areas of dense scar \( (<0.1 \text{ mV and } >85\% \text{ scar transmurality by MRI}) \) \( (n=3 \) patients); and (3) connecting dense scar \( (<0.1 \text{ mV and } >85\% \text{ transmurality}) \) to electrically nonconducting structures, such as mitral valve ring \( (n=6 \) patients). More than 1 linear ablation strategy was applied in some patients.

No procedure-related complications were observed. After 15\pm12 months follow-up, 54\% of patients had nonsustained or sustained VT documented by ICD interrogation (time to first occurrence, 5\pm4 months postablation). Appropriate ICD shocks were seen in 4 of the 14 patients. ICD shocks occurred in 2 patients during a heart failure exacerbation, which resulted ultimately in the patients’ deaths 1 week and 20 months after ablation. One patient underwent a second ablation, and 1 was treated medically.

**Discussion**

The findings of this study are that (1) CE-CMR can be safely performed in selected patients with ICD; (2) ICD artifact decreases imaging quality but allows the detection of myocardial MRI scar in the majority of patients; (3) 3D LV anatomy and reconstructed MRI-derived scar can be accu-
rately registered with clinical mapping systems; (4) MRI-derived scar provides anatomic guidance during mapping and VT ablation; and (5) in combination with 3D intracardiac echocardiography, allows the visualization of ablation lesions as shown in Figure 8. MRI demonstrates the scar substrate extracted from the MRI sequences, and 3D US demonstrates the newly placed ablation lesion in the area of MRI scar.

**Safety and Diagnostic Yield of CMR in Patients With ICDs**

Although most patients requiring VT ablations have ICDs, defibrillators are still considered a contraindication for MRI as reflected by a recent Food and Drug Administration summary statement. Whereas early reports demonstrated potential software and hardware failure with clinical complications, more
recent phantom, animal, and patient series suggested that MRI could be performed safely with appropriate ICD and patient selection. However, only a minority of MRIs in these studies were performed for dedicated cardiac imaging. To our knowledge, this study is the largest of CMR (n = 22) performed in patients with ICDs. No complications were seen with limited SAR of <2.0 W/kg.

Gimbel et al. reported a power on reset in 1 of 7 patients with ICDs undergoing nonthoracic MRI (SAR not specified). Nazarian et al. found no complications in 13 patients with CMR out of 24 ICD patients with thoracic and extrathoracic MRI (SAR <2 W/kg). Naehle et al. recently reported on MRI in 18 patients with ICDs (4 patients with CMR) (SAR ≤2 W/kg), finding an acute decrease of battery voltage that recovered at follow-up. LGE MRI has been shown to accurately determine areas of myocardial necrosis, but imaging quality is affected by ICD-induced geometric distortion, warping, and susceptibility-induced artifacts.

In the present study, ICD artifacts significantly limited the detection of myocardial scar in the anterior wall and depended on imaging plane and low implant location parts of the septal; lateral; and, rarely, inferior wall. However, LGE representing MRI scar could be visualized in all patients. The anatomic-dynamic and perfusion imaging sequences were less susceptible to ICD artifacts and may allow for the further characterization of the anterior wall scar substrate based on anatomic (eg, wall thinning), dynamic (eg, hypocontractility), and first-pass perfusion (hypoenhancement) characteristics, but this was not performed in this study.

**Feasibility of Image Integration of 3D MRI-Derived Scar**

Reconstruction of representative 3D scar models from 2D and 3D image sequences was possible in all cases. Integration and registration of the 3D-reconstructed MRI scar into the clinical mapping system was successfully performed in all patients.
The final registration accuracy was 3.9±1.8 mm, which is similar to previously reported image integration studies.\textsuperscript{18–20} Codreanu et al\textsuperscript{21} and Desjardins et al\textsuperscript{19} retrospectively reconstructed and registered postinfarct MRI scar with previously acquired voltage maps. Bogun et al\textsuperscript{18} registered MRI scar in 14 patients without ischemia in preparation for VT or premature ventricular complex ablation. All these studies used patients without ICDs and found a good correlation between abnormal voltage and (especially endocardial) LGE.

**Supplementary MRI Substrate Characterization During VT Ablation**

To our knowledge, this is the first time that early registration approaches have been used to display intramural scar location and transmurality to guide the majority of LV mapping and ablation. An important finding of this approach is that \( \approx 4\% \) of mapping points with initial voltages of <1.5 mV were found to be due to suboptimal catheter contact and that simultaneous MRI scar display allowed for instantaneous correction, resulting ultimately in a more accurate substrate characterization. This finding is consistent with those of Codreanu et al,\textsuperscript{21} who reported in 3 (25\%) of 12 patients a >20\% larger scar by voltage criteria (<1.5 mV) than by MRI, which they attributed to likely difficult catheter contact.\textsuperscript{21}

Another important result of the present study is that in >60\% of our patients, the early display of the MRI border zone combined with the 12-lead VT morphology allowed the identification of \( \approx 11/12 \) pace map sites before detailed voltage mapping (normally required to determine the border zone and pace map sites). This finding is consistent with other studies that found that successful ablation sites in ischemic VT were located in 68\% at the scar border zone.\textsuperscript{22} Additionally, not only the display of the lateral border zone, but also the 3D integration of alive myocardium within a larger area of scar (eg, surviving PM) was able to visually guide successfully pace mapping before complete voltage mapping and may enable a faster, anatomically guided ablation approach.

Furthermore, 3D MRI scar integration provided visualization of the midmyocardial scar, functioning as the VT
reentrant substrate that was not detected by conventional voltage criteria. The midmyocardial scar display anatomically guided pace mapping and provided the rationale to ablate in an endocardial site with normal voltage and signal characteristics that successfully eliminated the clinical tachycardia. In the present study, a >2-mm rim of surviving endocardium was able to prevent the detection of up to ~60% transmural midmyocardial scar using conventional voltage criteria. Correspondingly, bipolar amplitudes of midmyocardial and epicardial scar were found in patients with ischemia to be 1.52 ± 1.41 mV.

Differences between MRI scar and voltage-defined scar also have been reported in other studies. Twenty-percent larger MRI scar than voltage scar was found by Codreanu et al21 in the inferobasal LV wall. Desjardins et al19 reported normal electrogram characteristics in areas with 5±18% transmural scar. Similarly, we found that endocardial MRI scar of <25% transmurality might not be detected by voltage mapping. This limitation of voltage mapping to detect thin layers of scar also may help to explain successful VT ablations in myocardium with normal voltage amplitudes in 4% of patients. 22

In this study, successful ablation sites displayed a scar transmurality of 68±26% and were frequently adjacent to areas of <25% scar transmurality. This finding is consistent with previous studies in patients with ischemia that found a scar transmurality of 60±38% at successful ablation sites19 and a preferential location in the border zone area. Similarly, LGE was seen at all ablation sites of LGE-positive patients with nons ischemic cardiomyopathy.18

In the present study, the final decision about the ablation site relied on conventional parameters like pace mapping or concealed entrainment, which likely explains the similar results to nonimage-guided VT ablation studies.9 With improving protocols, predictive MRI characteristics of successful ablation sites could potentially be developed. In a canine model, Ashikaga et al21 demonstrated that high-resolution MRI was able to delineate areas of surviving myocardial areas within scar that correlated with VT channels during epicardial mapping. Several mathematical models exist that may be able to predict VT channels and successful ablation sites based on the infarct border zone geometry.20

Limitations

Although in this small sample of ICD patients MRI did not result in adverse events, this needs to be confirmed in larger patient cohorts and various imaging protocols. ICD artifacts prevented the detection of LGE in the anterior wall and possibly other parts of the LV. Complementary anatomic-dynamic or perfusion imaging, which is less susceptible to those artifacts, could be used to provide additional information about those areas. Alternatively, fusion imaging (eg, PET and MRI) could help to define the presence of anterior scar.

Although careful image registration was performed, misregistrations cannot be excluded. However, the used registration algorithms have been validated in previous studies, and the overall registration accuracy was comparable to other reports, suggesting no significant additional error. 18–20

The study population included patients with predominantly ischemic but also nonischemic cardiomyopathy. However, this heterogeneity would be unlikely to affect the MRI safety profile of ICDs. Although scar distribution frequently is different in both entities, only patients with LGE scar were used for 3D MRI scar registration, and LGE was found to be a critical component of all successful ablation sites.

Conclusions

Three-dimensional MRI scar maps of patients with ICDs can be successfully extracted and registered and provide an improved appreciation of the complex scar anatomy compared with voltage mapping alone. The early MRI scar display can assist in more accurate scar delineation and mapping and provide anatomic guidance for identification of critical scar substrate in many patients. Its impact on clinical parameters, such as procedure times and long-term success, will need to be assessed in future randomized controlled trials.

Acknowledgments

We thank Tom O’Donnell, PhD (Siemens Corporate Research, New York), for his excellent technical support and software expertise.

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Disclosures

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References


**CLINICAL PERSPECTIVE**

Ablation of ventricular tachycardia (VT) frequently is required in patients with recurrent implantable cardioverter-defibrillator (ICD) shocks. MRI would be uniquely positioned to characterize the complex scar substrate, which is the target of most VT ablations. However, safety of patients with ICDs and ICD artifacts on imaging quality are of clinical concern. This study demonstrates in the so-far largest published ICD cohort that cardiac MRI can be safely performed in selected patients with ICDs. Although the ICD artifacts were especially pronounced in the anterior left ventricular wall, they allowed the identification of relevant ventricular scar in all patients. Importantly, a detailed 3D model of the myocardial scar could be reconstructed and registered with the clinical mapping system to provide guidance during the VT ablation. It allowed the detection of falsely low voltage points due to suboptimal catheter contact and avoided potentially unnecessary ablation lesions. Reconstructed 3D scar images allowed the identification of successful ablation sites with only limited pace mapping in >60% of patients. Additionally, 3D MRI scar display allowed successful ablation of VT originating from a midmyocardial scar substrate, which could not be detected by voltage mapping criteria. Furthermore, surviving myocardium within left ventricular scar representing successful ablation sites could be visualized using MRI reconstructions. Successful ablation sites tended to be in the transition zones of >50% to <25% transmurality, which may allow a new imaging-guided approach to substrate-guided VT ablation.
MRI-Guided Ventricular Tachycardia Ablation: Integration of Late Gadolinium-Enhanced 3D Scar in Patients With Implantable Cardioverter-Defibrillators
Timm Dickfeld, Jing Tian, Ghada Ahmad, Alejandro Jimenez, Aharon Turgeman, Richard Kuk, Matthew Peters, Anastasios Saliaris, Magdi Saba, Stephen Shorofsky and Jean Jeudy

_Circ Arrhythm Electrophysiol_. 2011;4:172-184; originally published online January 26, 2011; doi: 10.1161/CIRCEP.110.958744

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<th>Voltage area &lt;0.5mV [cm²]</th>
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<th>CL [ms]</th>
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Data Supplement 2: Image-Guided Ventricular Tachycardia Ablation. Dickfeld et al.
**Supplement 2**: Individual Procedural and Imaging Patient Data. To allow valid comparison between MRI scar and voltage scar, area of ICD artifact was excluded for scar area analysis.

Relevant Abbreviations: P# - patient number; mid – midmyocardial; (A) – predominant artifact; CL – cycle length of ventricular tachycardia; * - Ventricular tachycardia targeted during ablation (RFA)
Supplement 1. ICD system specifications for individual patients. Ventricular lead denotes right ventricular ICD leads. Coronary sinus leads identified with (LV).