Remote Magnetic Navigation to Guide Endocardial and Epicardial Catheter Mapping of Scar-Related Ventricular Tachycardia

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Background—The present study examines the safety and feasibility of using a remote magnetic navigation system to perform endocardial and epicardial substrate-based mapping and radiofrequency ablation in patients with scar-related ventricular tachycardia (VT).

Methods and Results—Using the magnetic navigation system, we performed 27 procedures on 24 consecutive patients with a history of VT related to myocardial infarction, dilated cardiomyopathy, arrhythmogenic right ventricular cardiomyopathy, hypertrophic cardiomyopathy, or sarcoidosis. Electroanatomic mapping of the left ventricular, right ventricular, and ventricular epicardial surfaces was constructed in 24, 10, and 12 patients, respectively. Complete-chamber VT activation maps were created in 4 patients. A total of 77 VTs were inducible, of which 21 were targeted during VT with the remotely navigated radiofrequency ablation catheter alone. With a combination of entrainment and activation mapping, 17 of 21 VTs (81%) were successfully terminated in a mean of 8.4±8.2 seconds; for the remainder, irrigated radiofrequency ablation was necessary. The mean fluoroscopy times for endocardial and epicardial mapping were 27±23 seconds (range, 0 to 105 seconds) and 18±18 seconds (range, 0 to 49 seconds), respectively. In concert with a manually navigated irrigated ablation catheter, 75 of 77 VTs (97%) were ultimately ablated. Four patients underwent a second procedure for recurrent VT, 3 with the magnetic navigation system. After 1.2 procedures per patient, VT did not recur during a mean follow-up of 7±3 months (range, 2 to 12 months).

Conclusions—The present study demonstrates the safety and feasibility of remote catheter navigation to perform substrate mapping of scar-related VT in a wide range of disease states with a minimal amount of fluoroscopy exposure. (Circulation. 2007;115:1191-1200.)

Key Words: ablation ■ catheter ablation ■ electrophysiology ■ magnetic resonance imaging ■ mapping ■ tachycardia ■ tomography

Significant advances have been made in catheter ablation of scar-related ventricular tachycardia (VT). These advances are due in part to an improved understanding of the pathophysiology governing these tachyarrhythmias and to technological advances such as electroanatomic mapping (EAM) systems. This advancement has led to a paradigm shift in the strategy by which VT is mapped and ablated: substrate-based catheter ablation.1–4 Instead of mapping during VT, this approach involves identifying and ablating the arrhythmogenic myocardium predominantly during sinus rhythm. Although effective, this approach is limited by the need for a degree of ventricular mapping accuracy and detail that requires advanced operator skill with catheter manipulation.

Clinical Perspective p 1200

When used in concert with a compatible EAM system, remote navigation technology may facilitate cardiac mapping and ablation independently of operator dexterity. The magnetic navigation system (MNS) uses highly flexible catheters equipped with small magnets embedded in the tip for catheter orientation with an external magnetic field. To date, this platform system has been used in mapping and ablation of accessory pathways in patients with AV nodal or AV reentrant tachycardia and in the treatment of atrial fibrillation.5–7 The present study examines the hypothesis that substrate-based endocardial and epicardial remote magnetic mapping and ablation can be safely and effectively performed in patients with scar-related VT.

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Methods

The present study was approved by the Massachusetts General Hospital Institutional Review Board Committee and performed according to institutional guidelines.

Patient Population

Between November 2005 and October 2006, a total of 27 procedures were performed on 24 consecutive patients with a history of scar-related VT. The cause of VT substrate was diverse: post-myocardial infarction (MI), dilated cardiomyopathy, arhythmogenic right ventricular (RV) cardiomyopathy, hypertrophic cardiomyopathy, and sarcoidosis. Twenty of 27 procedures (74%) were performed under general anesthesia; the remainder were done under only moderate sedation. In 18 procedures (67%), intra-aortic balloon pump counterpulsation was used for either prophylaxis against worsening heart failure or hemodynamic stabilization during arrhythmia induction and mapping. All intra-aortic balloon pumps were removed immediately at the completion of the procedure.

Remotely Guided MNS

The remotely controlled catheter navigation system used in the present study consists of 2 independent but communicating components: the Niobe Stereotaxis MNS (Stereotaxis, Inc, St Louis, Mo) and a prototype EAM system (CARTO-RMT, Biosense Webster, Inc, Diamond Bar, Calif). The MNS uses 2 large magnets positioned on either side of the procedure table to generate a composite magnetic field for directional catheter orientation, as described previously.5–7 The CARTO-RMT EAM platform is a prototype magnetic localization system similar to the standard CARTO system2; the major important difference is its ability to localize the ablation catheter without interference from the MNS magnetic field. This EAM system can localize both standard CARTO and the specialized CARTO-RMT catheters. Accordingly, EAM can be performed either in the conventional fashion with manual catheter manipulation or remotely with the MNS.

The EAM system and the MNS communicate in a unidirectional fashion. Three-dimensional locations can be prescribed on the EAMs for transfer to the MNS. The MNS then calculates the vector required of the magnetic field to orient the catheter in this direction. If the catheter fails to move to the desired location because of obstacles in its path (eg, trabeculae, chordae tendineae, papillary muscles), the operator can simply withdraw the catheter remotely to free it of the obstacle(s) and then re-advance to the desired location. Alternatively, the magnetic field can be remotely manipulated to incrementally manipulate the catheter. The communication between the CARTO-RMT EAM and the MNS provides a synchronized view of the heart so that free hand manipulations of this magnetic vector can be performed to iteratively move the catheter along the cardiac surface (Figure 1).

Cardiac Chamber Mapping and Radiofrequency Ablation

A transseptal puncture was performed under the guidance of fluoroscopy and, if available, intracardiac echocardiography, and an 8.5F Mullins sheath was placed near the mitral valve plane. Intravenous heparin was administered just before transseptal puncture. Left ventricular (LV) substrate mapping was performed with a combination of transseptal and retrograde aortic approaches in all patients; endocardial RV mapping was performed with femoral venous access. In selected patients, epicardial mapping was performed with the percutaneous subxiphoid needle puncture technique.9–11

Two types of catheters were used for mapping and ablation: a remotely guided, 4-mm-tip, quadripolar (RMT) catheter with 3 embedded magnets to align with the MNS-generated magnetic field (Navistar-RMT, Biosense-Webster, Inc) and a manually directed, externally irrigated, 3.5-mm-tip catheter (Thermocool, Biosense-Webster, Inc). For the last 15 procedures, the RMT catheter had a thermocouple embedded in its tip for temperature monitoring.

Programmed stimulation included up to 3 extrastimuli and rapid pacing from 2 ventricular sites (right or left, depending on the location of the scar) to document cycle lengths and 12-lead ECG morphologies of all inducible VTs. In all patients, baseline ventricular substrate-based mapping was performed remotely with the MNS and the RMT mapping catheter. Mapping consisted of constructing 3-dimensional electroanatomic voltage maps of the chamber(s) of interest (LV, RV, and/or ventricular epicardial surface) during sinus rhythm or RV pacing, displaying peak-to-peak bipolar electrogram amplitude with a fill threshold of at least 15 and 20 mm for endocardial and epicardial maps, respectively. As previously described, a bipolar electrogram voltage amplitude >1.5 mV was defined as normal myocardium in post-MI patients.11–14 For other pathologies, the amplitude scales were adjusted to best identify the diseased myocardial tissue.11–14 Fluorescence exposure times during ventricular chamber mapping were recorded in most patients. The chamber mapping time was defined as the time elapsed starting just after the RMT catheter was placed into the relevant chamber and ending after the chamber map was completed just before radiofrequency ablation was begun. After detailed mapping to fully define the scar borders, ventricular activation and entrainment mapping during sustained VT was performed. In a few selected patients with sustained hemodynamically stable VT, full-chamber activation maps were generated; most underwent partial activation mapping only.

In all patients, a combination of entrainment, late potential, and pace mapping was used during substrate mapping. Briefly, if a hemodynamically stable VT was inducible (stable for even a few seconds), standard entrainment maneuvers were used to identify and ablate the critical pathway of the circuit. Typically, the RMT catheter was used to deliver these radiofrequency applications remotely along the endocardial and/or epicardial surfaces. Power titration was based on impedance monitoring or, when available, temperature monitoring to achieve 55°C to 65°C and 65°C to 85°C for endocardial and
epicardial lesions, respectively. If the arrhythmia(s) failed to terminate or remained inducible after ablation with the RMT catheter, a manual irrigated catheter was used to eliminate the VT. In addition, the manual catheter was used in most patients to ablate additional remaining putative target sites such as late potentials, pace map sites with a good QRS match to an inducible VT and a long stimulus to QRS time, and VT exit sites identified by pace mapping along scar borders. With the manual catheter, power was titrated to achieve an impedance fall of \(-10\%\). The postablation stimulation protocol included at least as aggressive a stimulation protocol as that used to initially induce the VTs at the beginning of the procedure.

Follow-Up
VT recurrence was identified by history and clinical symptoms and through device interrogation. All patients received anticoagulation with warfarin or aspirin after the procedure. Antiarrhythmic drug therapies that patients had been prescribed long term were either continued at the same or reduced dosage or, in selected cases, discontinued. Antiarrhythmic agents that had been initiated recently therapies in a 24-hour period. Four patients (17%) had a history incessant VT or ICD storm, defined as \(-3\) appropriate ICD

Results

Patient Characteristics
A total of 27 procedures were performed on 24 consecutive patients with a history of scar-related VT. Patient characteristics are shown in Table 1. The mean age of the study cohort was \(61 \pm 15\) years (range, 21 to 83 years). Twenty-one patients (87%) were men. The mean LV ejection fraction as assessed by echocardiography was \(37 \pm 18\%\) (range, 15% to 83%), with a mean LV dimension of \(57 \pm 11\) mm (range, 40 to 77 mm) at end diastole and \(46 \pm 13\) mm (range, 22 to 69 mm) at end systole. Eleven patients (46%) had advanced heart failure as defined by a New York Heart Association functional class III or IV. The origin of VT substrate was related to MI in 15 patients (62%), dilated cardiomyopathy in 3 (13%), arrhythmogenic RV cardiomyopathy in 3 (13%), hypertrophic cardiomyopathy in 2 (8%), and sarcoidosis in 1 (4%). Nineteen patients (79%) had an ICD. In addition, 19 patients (79%) were receiving antiarrhythmic drug therapy. All patients had symptomatic or recurrent monomorphic VT; ICD therapy or cardioversion was required in 19 cases (79%). Fifteen of 24 patients (62%) presented with either incessant VT or ICD storm, defined as \(\geq 3\) appropriate ICD therapies in a 24-hour period. Four patients (17%) had a history of previously failed VT ablation using a conventional approach (ie, not using remote navigation). All patients had evidence of at least a single VT morphology on a 12-lead ECG or stored ICD electrograms.

Mapping Approach
In 24 of 27 procedures, LV endocardial mapping was performed via both transseptal and retrograde aortic approaches.

### TABLE 1. Clinical Characteristics of Patients Undergoing Remote Mapping and Ablation

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age, y</th>
<th>LVEF, %</th>
<th>NYHA HF Class</th>
<th>VT Substrate</th>
<th>ICD</th>
<th>AAD</th>
<th>History</th>
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</thead>
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<td>27</td>
<td>IV</td>
<td>MI</td>
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<td>A, BB</td>
<td>Syncope, slow incessant MMVT, DCCV</td>
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<td>34</td>
<td>III</td>
<td>DCM</td>
<td>Yes</td>
<td>BB</td>
<td>Near syncope, sustained MMVT, ICD storm</td>
</tr>
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<td>15</td>
<td>III</td>
<td>MI</td>
<td>Yes</td>
<td>A, BB</td>
<td>Symptomatic sustained MMVT</td>
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<tr>
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<td>49</td>
<td>45</td>
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<td>MI</td>
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<td>BB</td>
<td>MMVT degenerated into PMVT, ICD storm</td>
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<tr>
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<td>75</td>
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<td>MI</td>
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<td>BB</td>
<td>Symptomatic MMVT</td>
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<tr>
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<td>49</td>
<td>45</td>
<td>IB</td>
<td>MI</td>
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<td>BB</td>
<td>Sustained MMVT, ICD storm, prior failed RFA</td>
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<tr>
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<td>Yes</td>
<td>BB, M</td>
<td>Recurrent MMVT, ICD storm, prior failed RFA</td>
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<tr>
<td>8</td>
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<td>53</td>
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<td>A, F, S</td>
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<td>76</td>
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<td>MI</td>
<td>Yes</td>
<td>BB, M</td>
<td>Recurrent MMVT, ICD therapy</td>
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<td>30</td>
<td>IB</td>
<td>Sarcoidosis</td>
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<td>M, S</td>
<td>Symptomatic sustained MMVT, ICD storm</td>
</tr>
<tr>
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<td>62</td>
<td>30</td>
<td>III</td>
<td>MI</td>
<td>Yes</td>
<td>A, BB</td>
<td>Near syncope, sustained MMVT, ICD therapy</td>
</tr>
<tr>
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<td>II</td>
<td>MI</td>
<td>Yes</td>
<td>A, BB</td>
<td>Syncope, recurrent MMVT, ICD storm</td>
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<td>83</td>
<td>IB</td>
<td>HCM</td>
<td>Yes</td>
<td>S</td>
<td>Recurrent MMVT, ICD storm</td>
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<td>BB, M</td>
<td>Symptomatic sustained MMVT, ICD storm</td>
</tr>
<tr>
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<td>65</td>
<td>20</td>
<td>III–IV</td>
<td>DCM</td>
<td>Yes</td>
<td>A, BB, M</td>
<td>Symptomatic sustained MMVT, ICD storm</td>
</tr>
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<td>III–IV</td>
<td>MI</td>
<td>Yes</td>
<td>A, BB, M</td>
<td>MMVT, ICD therapy</td>
</tr>
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<td>69</td>
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<td>MI</td>
<td>Yes</td>
<td>BB</td>
<td>Recurrent MMVT, ICD storm</td>
</tr>
<tr>
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<td>64</td>
<td>55</td>
<td>II</td>
<td>MI</td>
<td>No</td>
<td>A, BB</td>
<td>Symptomatic MMVT</td>
</tr>
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<td>19</td>
<td>72</td>
<td>20</td>
<td>III–IV</td>
<td>MI</td>
<td>Yes</td>
<td>BB, S</td>
<td>Recurrent MMVT, ICD storm</td>
</tr>
<tr>
<td>20</td>
<td>53</td>
<td>42</td>
<td>II</td>
<td>DCM</td>
<td>No</td>
<td>A, BB, M</td>
<td>Symptomatic recurrent MMVT</td>
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<td>21</td>
<td>70</td>
<td>IB</td>
<td>HCM</td>
<td>Yes</td>
<td>BB, M</td>
<td>Recurrent PMVT, ICD therapy</td>
</tr>
<tr>
<td>22</td>
<td>64</td>
<td>61</td>
<td>IB</td>
<td>ARVC</td>
<td>No</td>
<td>M, S</td>
<td>Symptomatic MMVT (below ICD detection zone), DCCV, prior failed RFA</td>
</tr>
<tr>
<td>23</td>
<td>62</td>
<td>20</td>
<td>II</td>
<td>MI</td>
<td>Yes</td>
<td>BB, M</td>
<td>Incessant MMVT, ICD storm</td>
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<tr>
<td>24</td>
<td>81</td>
<td>15</td>
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<td>MI</td>
<td>Yes</td>
<td>A, BB</td>
<td>Symptomatic slow incessant MMVT (below ICD detection zone)</td>
</tr>
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</table>

LVEF indicates LV ejection fraction; NYHA HF, New York Heart Association heart failure; AAD, antiarrhythmic drug; A, amiodarone; BB, \(\beta\)-blocker; F, flecainide; M, mexiletine; S, sotalol; MMVT, monomorphic VT; DCCV, external direct current cardioversion; DCM, dilated cardiomyopathy; RFA, radiofrequency ablation; PMVT, polymorphic VT; ARVC, arrhythmogenic RV cardiomyopathy; and HCM, hypertrophic cardiomyopathy.
LV mapping was not performed in 2 arrhythmogenic RV cardiomyopathy patients (patients 8 and 14) and during the initial procedure on the patient with sarcoidosis (patient 10–1). RV endocardial mapping was performed using a long sheath advanced to the approximate plane of the tricuspid valve for stabilization. Pericardial access was successful in 13 of 16 patients (81%), including 2 patients with prior cardiac surgery. Pericardial access could not be achieved in the remaining patients because of previous cardiac surgery (1 patient) or the presence of pericardial adhesions resulting from prior MI (1 patient) or sarcoidosis (1 patient).

Remote Substrate-Based Ventricular Mapping
Maps of LV and RV endocardium and ventricular epicardium were constructed in 24, 10, and 12 procedures, respectively. The mean LV and RV chamber and pericardial space volumes were 220±104, 264±111, and 651±145 cm³, respectively. The mean total points collected during mapping of LV and RV endocardium and ventricular epicardium were 142±75, 76±73, and 123±37, respectively. Of these, the mean points collected with the RMT catheter were 111±67 (78%), 74±63 (97%), and 122±34 (99%), respectively. Remote mapping of these chambers required a mean duration of 84±44 minutes (48±18 seconds per point), 66±48 minutes (42±18 seconds per point), and 75±34 minutes (36±12 seconds per point), respectively. As shown in Table 2, the fluoroscopy times required to perform endocardial and epicardial remote mapping were 27±23 seconds (range, 0 to 105 seconds) and 18±18 seconds (range, 0 to 49 seconds), respectively; the total fluoroscopy time to complete remote mapping was 34±32 seconds (range, 1 to 136 seconds). The total procedural fluoroscopy time was 21±7 minutes (range, 9 to 33 minutes). Bipolar ventricular voltage amplitude maps were generated in all patients. Abnormal ventricular scar tissue, defined by low-voltage electrogram amplitude, was seen in all but 3 patients. Examples of ventricular EAMs constructed in patients with post-MI, arrhythmogenic RV cardiomyopathy, and hypertrophic cardiomyopathy–related VTs are shown in Figures 2 and 3.

TABLE 2. Results of Arrhythmia Induction and Fluoroscopy Usage Time During Mapping and Ablation

<table>
<thead>
<tr>
<th>Patient</th>
<th>SVT, n</th>
<th>CLs of Induced VTs, ms</th>
<th>Total Fluoroscopy Time, min</th>
<th>Endocardial, s</th>
<th>Epicardial, s</th>
<th>Total, s</th>
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<td>13</td>
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<tr>
<td>3–1*</td>
<td>2</td>
<td>524, 405</td>
<td>24</td>
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<tr>
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<td>16</td>
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</tr>
<tr>
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<td>280, 220</td>
<td>16</td>
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<tr>
<td>6</td>
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<td>295 (NSVT)‡</td>
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</tr>
</tbody>
</table>

SVT indicates sustained VT; CL, cycle length; NSVT, nonsustained VT; and N/A, data not available.
*First mapping and ablation procedure for this patient.
†Second mapping and ablation procedure for this patient.
‡Induction of nonsustained VT only.
VT Induction and Catheter Ablation

A total of 77 VTs were inducible during 23 of 27 procedures (85%), whereas in 4 patients (patients 2, 6, 13, and 21), sustained monomorphic VT could not be induced (Table 2). In 1 of these 5 patients (patient 6), nonsustained monomorphic VT was induced repeatedly and thus targeted for ablation. Although no VTs were inducible in the other 3, in 1 patient (patient 2), typical atrial flutter was induced repeatedly and eliminated by cavotricuspid isthmus ablation. During sustained hemodynamically stable VT, full-chamber activation mapping was performed in 4 patients during 5 procedures, and partial activation mapping was performed in the remaining. Entrainment mapping was performed in 20 procedures. Pace mapping and targeting of late and fractionated potentials were used in 20 and 23 procedures, respectively. Figures 4 and 5 illustrate examples of substrate mapping and ablation in patients with hemodynamically stable and unstable VTs.

Of the 77 inducible VTs, 21 were targeted for ablation during VT with the remote catheter. Of these, a total of 17 VTs (81%) were successfully terminated during the remote catheter alone, whereas in 22 procedures, the manual, irrigated catheter was used to enhance procedural safety and efficacy. In concert with the latter catheter, 75 of 77 VTs (97%) were eliminated altogether. The mean total duration of radiofrequency delivery per procedure was 26±11 minutes. The mean total radiofrequency lesions delivered with the remote and manual catheters were 8±8 and 24±12 (total, 31±12), respectively. During 4 procedures (patients 3–1, 4, 9, and 17), VT was not inducible at the end of the procedure, the patient presented with another VT that was also remotely mapped as traversing this channel, but in the opposite direction. During the second procedure, this channel was completely ablated with irrigated radiofrequency energy to eliminate VT; no VT recurred after this second procedure. Also shown are electroanatomical activation (C & D) and voltage (E) maps during VT (cycle length of 550 ms) in a patient with arrhythmogenic right ventricular cardiomyopathy (#8). Half of the tachycardia cycle length was mapped in this patient. A diastolic potential is seen in the inset; at this location, entrainment with concealed fusion and a post-pacing interval equal to 550 ms was observed. Endocardial ablation terminated the VT, but it was re-inducible; epicardial ablation at the opposite site completely eliminated the VT.

Complications

The 30-day mortality from the procedure was zero. One patient (patient 7) with prior cardiac surgery who underwent
pericardial mapping with the manual catheter developed a loculated pericardial effusion in the posterior aspect of the left atrium with partial compression requiring surgical pericardial decompression. One patient (patient 22) who underwent RV epicardial mapping only (no LV endocardial mapping) developed transient right ulnar nerve palsy after the procedure. It was unclear whether the palsy represented an embolic stroke or was the result of prolonged immobilization under general anesthesia. Another patient (patient 23) developed uncomplicated bilateral lower-extremity deep venous thrombosis that was successfully treated with anticoagulation. Finally, 1 patient (patient 1) died more than a month after the procedure as a result of advanced, medication-refractory heart failure.

Follow-Up
During follow-up, repeat VT ablation was required in 4 patients. One patient (patient 17) with prior cardiac surgery continued to have recurrent VT associated with ICD discharges and underwent successful epicardial ablation with a manual approach after minimally invasive surgical subxiphoid access to the pericardial space.15 The other 3 patients (patients 3, 10, and 18) presented with slow VT without ICD discharges and underwent successful repeat VT ablation with the MNS. During follow-up, inappropriate ICD discharges occurred in 1 patient (patient 9) as a result of atrial fibrillation. In toto, there were no VT events after a mean follow-up of 7±3 months (range, 2 to 12 months). On the other hand, if assessed after a single procedure only, procedural success was achieved in 20 of 24 patients (83%).

Discussion
A number of advances have been made in recent years in catheter ablation of complex arrhythmias. Nevertheless, manipulation of ablation catheters during substrate-based mapping of scar-related VT requires adequate experience and manual dexterity and can be limited by the technical skill required for detailed mapping of ventricular myocardium. By obviating this skill requirement, remotely controlled magnetic/robotic navigation systems may enhance catheter-directed arrhythmia mapping and ablation. Magnetic navigation of cardiac catheters was first reported over a decade ago in a neonate with complex congenital heart disease in whom it was shown to enhance catheter guidance and manipulation.16 Since then, similar systems have been used safely in a variety of invasive cardiovascular procedures, including ablation of supraventricular cardiac arrhythmias.5–7

The present study demonstrates the safety and efficacy of endocardial and epicardial substrate mapping of VT with the MNS in the setting of a variety of cardiac pathologies. In addition to mapping, a subset of these patients also underwent ablation in the LV and RV chambers and the pericardial space. In toto, this remote navigation system proved capable of each of the 3 major components of substrate-based mapping and VT ablation: (1) delineating and identifying the diseased myocardium, (2) performing the necessary electrophysiological maneuvers required to identify the arrhythmogenic zones within the scar critical for VT maintenance, and (3) in a subset of induced VTs, delivering radiofrequency energy to terminate VT.
Delineation and Identification of Diseased Myocardium

Accurate EAMs of the LV, RV, and ventricular epicardium could be constructed remotely in patients with a wide variety of disease states. The MNS-compatible RMT catheter offers several potential advantages over the conventional manual catheter during chamber mapping. Because its orientation is guided entirely by magnetic field and no deflection wires are required, the RMT catheter is softer than traditional deflectable catheters along its distal segment. This feature could result in several clinically significant benefits. First, it is possible that less endocardial trauma (a common occurrence during standard mapping, albeit of unclear clinical significance) would result from the use of an RMT catheter. In particular, the risk of remote cardiac perforation should be low. Second, the softer touch of the RMT catheter is likely to cause less deformation of cardiac chambers than manual mapping, potentially resulting in a more accurate rendering of cardiac chambers. Although the software for the CARTO-RMT system used in the present study did not support integration with 3-dimensional computer tomography/magnetic resonance imaging, it is possible that the registration process to perform image-guided therapy may be facilitated by a more precise rendering of the chamber volume. However, the absence of a comparative manual mapping group prevents us from making definitive conclusions on any these points.

Identification of Arrhythmogenic Zones Required for VT

To identify the arrhythmogenic zones within a scar, 4 mapping strategies commonly are used in clinical practice: activation mapping, entrainment mapping, late potential mapping, and pace mapping. Partial activation mapping was performed in all patients with sustained VT. Although not always required, full activation maps were generated during 5 procedures. Although the lack of comparative manual mapping precludes a definitive conclusion, our qualitative assess-

Figure 4. Remote mapping and ablation of hemodynamically stable VT. Shown are the clinical slow VT at 585 ms (A), inferior views of the electroanatomical activation (B) and voltage (C) maps during VT, and a cardiac computed tomography scan showing a calcified LV inferobasal scar (D) from a patient with post-MI VT (#1). E, At the start of an attempt at entrainment from an inferior wall site deep within the scar (denoted by the black arrow in panel B), the first paced beat terminated the VT without manifest global ventricular capture. F, Just apical to this site (denoted by the red arrow in panel B), stable diastolic potentials are seen during VT; entrainment with concealed fusion and a post-pacing interval equal to 585 ms were observed at this location. G, During remote radiofrequency ablation at this site, the VT was eliminated in <4 s of commencing energy delivery.

Third, there was a minimal amount of fluoroscopy use during remote MNS mapping, <1 minute in most cases, regardless of the mapping approach, endocardial or epicardial. This was related in a large part to use of the RMT catheter because it can be manipulated inside cardiac chambers with minimal concern for trauma. In addition, because the catheter tip can always be visualized in a real-time fashion by EAM, confirmation of position by fluoroscopy is rarely necessary. It is important to note that manual ablation was performed in most cases. Therefore, it is likely that additional reductions in total fluoroscopy will be realized once MNS-compatible, irrigated radiofrequency ablation catheters become available for clinical use. This could result in a marked reduction in radiation exposure for both patients and operators during these complex procedures.
ment was that catheter-induced premature ventricular beats were less common than typically observed during manual mapping. This clinical observation is consistent with our prior experience of a marked reduction in premature ventricular beats during remote mapping compared with manual mapping in an experimental porcine model of healed MI.17

Electrogram stability is important during ventricular mapping to perform electrophysiological pacing maneuvers such as entrainment and pace mapping. In the present study, remote mapping demonstrated the requisite catheter stability to provide stable beat-to-beat electrogram morphology and consistent endocardial or epicardial ventricular capture during pacing. This was true whether performed during sinus rhythm or VT for entrainment or pace mapping, respectively. Detailed chamber mapping also was feasible during sinus rhythm to identify late potentials.

Delivery of Radiofrequency Energy to Terminate VT

In a subset of the patient cohort, radiofrequency ablation with the MNS and RMT catheter could be performed safely and feasibly in the LV, RV, and epicardial space. The initial procedure proved successful in 20 of 24 patients (83%). Of the 4 patients with recurrences, 3 had a successful repeat ablation procedure with the MNS (2 requiring a combined endocardial/epicardial approach), whereas the fourth patient was ablated manually with a pericardial approach after surgical pericardial access.15 Seventeen VTs were successfully terminated in 15 procedures with radiofrequency application with the RMT catheter at a mean duration of 8.4 seconds. Of note, most terminations achieved by endocardial delivery of radiofrequency energy occurred in <10 seconds (in 9 of 13), whereas most epicardial ablations took longer to terminate. This is consistent with our previous observation and may in fact be related to the presence of epicardial fat serving as an insulating barrier to rapid and effective radiofrequency energy transmission to the target site. Although in 2 cases successful ablation was performed entirely with the RMT catheter alone, it should be emphasized that the manual irrigated catheter also was used in most the cases. The reason was the safety and efficacy limitations of standard 4-mm-tip ablation in left-sided cardiac chambers as a result of a higher thromboembolic potential, not a reflection of its maneuverability or stability. It remains to be determined whether the ablation process could have been completed entirely with an irrigated RMT catheter, a hypothesis that can be tested once this irrigated catheter becomes available for clinical use.

Study Limitations

First, the fluoroscopic visual field was partially compromised during the procedures. With the magnets in place, it is usually not possible to fluoroscopically visualize the entire ventricular cavity. This was also evident during pericardial mapping, which generally requires a larger field of visualization. Nonetheless, this did not prove to be a major limitation because the need for fluoroscopy is greatly minimized with EAM. Second, the present study was not a randomized comparison of the safety and efficacy of remote and manual mapping and ablation. It was designed predominantly to address the feasibility of remote ventricular mapping. Therefore, definitive conclusions comparing these approaches cannot be reached without a formal comparative study. This includes assessments of catheter stability, premature ventricular beat frequency, and endocardial trauma. Third, although certain technical limitations of manual mapping are overcome.

Figure 5. Mapping and ablation of hemodynamically-unstable VTs. Four hemodynamically-unstable VTs were induced in a patient with dilated cardiomyopathy-related VT (#20). Remote epicardial voltage mapping (top) revealed a large low-voltage area without the presence of late or fractionated potentials, most likely representing epicardial fat.25 The remote endocardial voltage map (bottom) revealed an anterior-septal scar with associated fractionated and late potentials (inset). Pace mapping (right panel) from this area resulted in a QRS morphology similar to the first VT and with a delay between the stimulus to QRS. Irrigated radiofrequency ablation of late and fractionated potentials and good pace map sites resulted in successful elimination of all inducible VTs. The relationship of the endocardial and epicardial EAMs is better appreciated in Movie II in the online-only Data Supplement.
with remote mapping, one must still master the other skills required to perform remote ventricular mapping, including maneuvering the somewhat complex software architecture of remote navigation. Fourth, although both retrograde and transseptal approaches were used during the present study, the transseptal approach was preferable because of the enhanced response of the catheter tip to remote advancement/retraction. That is, during movement of the catheter during retrograde aortic mapping, the “slack” of the catheter along the arch of the aorta results in a relatively slow response time for movement of the catheter tip, a phenomenon less pronounced with transseptal mapping. This requires, however, that the operator be familiar with the transseptal puncture technique.

Conclusions
The present study presents clinical evidence for the feasibility of remote catheter navigation to perform ventricular substrate-based mapping in humans in a wide range of disease pathologies. The enhanced maneuverability of the RMT catheter permitted accurate mapping of difficult-to-reach areas. The remote approach was safe and efficacious, and it was possible with a minimal amount of fluoroscopy time and radiation exposure to both patients and operators. By obviating the need for the advanced operator skill often required for detailed ventricular mapping, substrate-based VT mapping with this approach may become much more widespread and effective.

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Disclosures

Dr Reddy has served as a consultant to Biosense-Webster, Inc. Dr Ruskin has served on the Medical Advisory Board of Stereotaxis, Inc. The remaining authors report no conflicts.

References


CLINICAL PERSPECTIVE

Significant advances have been made in recent years in catheter ablation of scar-related ventricular tachycardia as a result of both (1) an improved understanding of its pathophysiology and (2) technological advances that aid in performing the procedure. In particular, substrate mapping, in which the ventricle is mapped predominantly during sinus rhythm, allows successful catheter ablation of virtually all ventricular tachycardias, regardless of their hemodynamic effect. Although highly effective, ventricular tachycardia ablation remains an uncommon procedure, in part because of the advanced operator skill required to perform detailed ventricular mapping. The present study provides clinical evidence for the safety and feasibility of remote catheter navigation in performing ventricular substrate mapping in a wide range of disease pathologies. Used in concert with a compatible electroanatomical mapping system, remote magnetic navigation technology proved capable of performing each of the 3 major components of substrate-based ventricular tachycardia ablation: (1) delineating and identifying endocardial and epicardial scarred tissue, (2) performing the necessary electrophysiological maneuvers required to identify those arrhythmogenic zones critical for maintaining tachycardia, and (3) delivering radiofrequency energy to terminate both endocardial and epicardial ventricular tachycardias. The enhanced maneuverability of the remotely navigated catheter using this system allowed accurate mapping of otherwise difficult-to-reach areas. Finally, the “soft touch” of the remotely guided catheter permitted this detailed ventricular mapping with minimal fluoroscopy use. Thus, by obviating the need for the advanced operator skill required for substrate mapping, remote navigation technology may result in more widespread and effective catheter ablation of ventricular tachycardia.
Remote Magnetic Navigation to Guide Endocardial and Epicardial Catheter Mapping of Scar-Related Ventricular Tachycardia
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