Electroanatomic Substrate and Outcome of Catheter Ablative Therapy for Ventricular Tachycardia in Setting of Right Ventricular Cardiomyopathy

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**Background**—To gain insight into the pathogenesis of right ventricular (RV) cardiomyopathy and ventricular tachycardia (VT), we determined the clinical and electroanatomic characteristics and outcome of ablative therapy in consecutive patients with (1) RV dilatation, (2) multiple left bundle-branch block (LBBB)–type VTs, and (3) an abnormal endocardial substrate defined by contiguous electrogram abnormalities.

**Methods and Results**—All 21 patients had detailed RV bipolar electrogram voltage mapping. Eighteen patients had simultaneous left ventricular (LV) mapping, including all 4 patients with right bundle-branch block (RBBB) VT. VT was ablated in 19 patients by use of focal and/or linear lesions with irrigated-tip catheters in 10 of 19 patients. Eighteen patients were men, age 47±18 years, and none had a family history of RV dysplasia. RV volume was 223±89 cm³. Electrogram abnormalities extended from perivalvular tricuspid valves (5 patients), pulmonic valves (6 patients), or both valves (10 patients). Electrogram abnormalities always involved free wall, spared the apex, and included the septum in 15 patients (71%). The area of abnormality was 55±37 cm² (range, 12 to 130 cm²) and represented 34±19% of the RV. In 52 of 66 LBBB VTs, the origin was from the RV perivalvular region. LV perivalvular low-voltage areas noted in 5 patients were associated with a RBBB VT origin. No VT recurred after ablation in 17 patients (89%) during 27±22 months.

**Conclusions**—In patients with RV cardiomyopathy and VT, (1) perivalvular electrogram abnormalities represent the commonly identified substrate and source of most VT, (2) LV perivalvular endocardial electrogram abnormalities and VT can occasionally be identified, and (3) aggressive ablative therapy provides long-term VT control. (Circulation. 2004;110:2293-2298.)

**Key Words:** tachycardia ■ cardiomyopathy ■ catheter ablation ■ mapping
The 21 patients included in the study had (1) RV enlargement as documented on echocardiography, (2) multiple (≥2) morphologies of LBBB VT, and (3) detailed electroanatomic maps with an area of discrete contiguous bipolar electrogram voltage abnormalities (amplitude, <1.5 mV).

Two patients with the diagnosis of idiopathic LV cardiomyopathy and LVT VT are also included in this report. Although these 2 patients presented with right bundle-branch block (RBBB) VT and evidence of LV dysfunction, both also had evidence of RV dilatation on the echocardiogram, inducible LBBB-type VT, and detailed RV endocardial maps in sinus rhythm. One of these patients also had detailed percutaneous epicardial mapping of the RV and LV regions. The second patient underwent cardiac transplantation for worsening heart failure, and we compared the gross pathological findings noted on the endocardium in the RV and LV with the electrogram abnormalities observed on RV and LV electroanatomic maps. These patients were included to provide additional information linking the pathogenesis between idiopathic LV cardiomyopathy and VT and the RV cardiomyopathy and VT described in the study population.

Clinical Characterization of Patients
Detailed family histories, clinical and ECG characteristics, and echocardiographic RV and LV size and function were assessed. MRI was not performed routinely because of the presence of an implantable defibrillator in 14 patients at the time of index evaluation.

Electrophysiological Evaluation
The study patients underwent electrophysiological evaluation after informed consent had been obtained. All procedures were performed according to the institutional guidelines of the University of Pennsylvania Health System. All patients underwent programmed stimulation that included up to triple extrastimuli from multiple ventricular sites using at least 2 drive cycle lengths.

Endocardial Mapping
All patients underwent detailed magnetic electroanatomic voltage mapping as previously described.9,12 RV endocardial mapping was performed in all 21 patients, with LV endocardial mapping in 18 of the patients. The mapping catheter (Navistar) had a 4-mm distal tip and 2-mm ring electrode with an interelectrode distance of 1 mm. The bipolar signals were filtered at 100 mm/s speeds on the CARTO (Biosense, Inc) system. The peak-to-peak signal amplitude of the bipolar electrogram was measured automatically. Electroanatomic mapping was performed during sinus rhythm in 17 patients and during RV paced rhythm in 4 patients.

The electrogram signals were displayed as color gradients on a 3D bipolar voltage map.9,12 Tricuspid and mitral valvular sites were identified by the fluoroscopic catheter tip positions at the ventricular base with discrete bipolar recordings that demonstrated both atrial and ventricular signals of approximately equal amplitude. The pulmonary valve was carefully identified by passing the mapping catheter into the pulmonary artery and slowly withdrawing it until an RV electrogram was identified. Valvular sites were given a “location only” tag to preclude their influence on the voltage map color display. Careful attention was paid to record multiple endocardial electrograms around valvular structures. To ensure adequate sampling and representation of the entire endocardial surface area, the Fill Threshold of the CARTO system was set at 20 mm. Intracavitary points were identified as abrupt indentations on the endocardial shell contour with associated sudden reductions in signal slew rate and were appropriately edited from the voltage maps.

VT Localization and Catheter Ablation
The 12-lead ECG morphology of all induced and spontaneous VTs was assessed to approximate the site of origin (see Figure 6).9,12 The VT mapping techniques included activation, entrainment, and pace mapping using standard criteria.9,12 The “site of origin” for mappable VT demonstrated presystolic activity and entrainment with concealed fusion and a return cycle length within 30 ms of VT cycle length. Termination with focal endocardial RF energy application was associated with these criteria. For VT that was not mappable, the site of origin was approximated by the site of pace mapping that generated QRS complexes similar to those of VT.9,12 Detailed activation mapping and entrainment mapping could not be performed, but limited activation and entrainment information was used to corroborate pace map information when available. For unmappable VT, radiofrequency ablation was performed as linear lesions based on the location of the best pace map, the location of valvular anatomic boundaries, and the substrate defined by the voltage mapping as previously described.9,12 Characteristically, linear lesions crossed through the site of the best pace map and extended from the most abnormal endocardium (<0.5 mV) to either the valve annulus or normal myocardium (≥1.5 mV).9,12 The efficacy of ablative therapy was assessed on the basis of inducibility of VT and clinical follow-up using implantable defibrillator interrogation to document arrhythmia recurrences.

Reference Values for Bipolar Voltage Mapping
Reference values for identifying abnormal bipolar electrogram signal amplitude in the RV and LV have been established using the Navistar catheter and the CARTO mapping system.9,12 In an attempt to adjust for factors such as hypertrophy and aging in our patient population, the reference value for bipolar electrogram amplitude used to identify “normal” endocardium in this study was set at 1.8 to 2.0 mV whenever we assessed size of LV endocardial scar and/or displayed RV and LV endocardial voltage maps simultaneously. For the display of the RV endocardial bipolar voltage maps only, a signal amplitude of >1.5 mV was categorized as normal and was represented by the color purple.12 Thus, abnormal endocardium on the voltage map displays was always represented by the nonpurple range of colors, with the most abnormal signal amplitude, defined as “dense scar” (consistent with signal amplitude <0.5 mV), represented by the color red (Figures 1 to 7).

Estimation of Abnormal RV Endocardium Using Endocardial Voltage Map
Abnormal RV endocardium was defined as areas of contiguous recordings with electrogram amplitude of ≤1.5 mV. The extent of

Figure 1. Bipolar voltage maps of RV and LV. Color scale identifies normal endocardium, purple color, and abnormal endocardium (signal amplitude, ≥1.8 mV), rest of color range. Markedly abnormal signals with an amplitude <0.5 mV are represented by red. Top, Bottom and left anterior oblique coronal views from patient without structural heart disease. Entire endocardium is purple, and only isolated noncontiguous signals are other colors (arrows). Bottom, Bottom and right posterior views from patient with RV cardiomyopathy and VT. LV is displayed as purple, but RV endocardium shows large area of abnormal bipolar electrograms extending from tricuspid and pulmonic valves. TV indicates tricuspid valve; MV, mitral valve; and PV, pulmonic valve.
abnormal endocardium was estimated by measuring contiguous areas of abnormal electrogram signals from computer-generated color images using previously described techniques. By using the same “area calculation” algorithms, the entire RV endocardial surface area can be estimated, and the percentage of abnormal endocardium can also be measured. A total segment of electrogram abnormalities of at least 10 cm² with multiple sample points was required for study inclusion because small areas of perivalvular low voltage can occasionally be identified in the absence of RV cardiomyopathy because of inadequate bipolar electrogram sampling. Of note, RV volume measurements were automatically calculated for all patients using the system’s software.

Statistics
All results were presented as mean±SD. A probability value of \( P<0.05 \) was considered statistically significant.

Results

Patient Population
There were 18 men and 3 women, with a mean age of 47±18 years (range, 18 to 79 years). All patients presented for evaluation of sustained VT. On echocardiographic imaging, all had evidence of RV enlargement, with 17 patients having moderately to severely decreased RV function. Average RV volume from voltage maps was 223±89 cm³. The baseline 12-lead ECG showed precordial T-wave inversion (V2 and V3) in 15 patients, epsilon waves in 14 patients, and RV paced rhythm in 4 patients. Only 1 patient had a normal baseline ECG. Patients had clinical diagnosis of ARVD/CM on the basis of their clinical arrhythmia, echocardiographic findings, and/or the marked resting 12-lead ECG abnormalities. In 19 of the 21 patients, catheter ablation was attempted because of recurrent VT episodes. All patients had implantable defibrillators (14 before and 7 after their index evaluation). LV function was normal in 11 patients and depressed in 10 patients, with an LV ejection fraction of 20% to 45%. Five patients had a history of LV heart failure.

No patient had a family history of ARVD/CM. In addition, none of the study patients had a family history of ventricular
wide range of 12 to 130 cm². These values represented by purple, signal amplitude >2.0 mV. Electrogram abnormalities extend from tricuspid and mitral valves (yellow arrows). Origin of VT based on activation and pace mapping was perivalvular mitral for RBBB VT and perivalvular tricuspid valve for LBBB VT (dashed lines).

Outcome of VT Mapping and Ablation

Nineteen of the 21 patients underwent catheter ablation of VT. Activation and entrainment mapping followed by focal ablation was used in 3 patients with only hemodynamically tolerated VT. In the remaining 16 patients with additional or only unmappable VT, linear lesions of 2.0 to 8.6 cm were also deployed, with the site of ablation guided primarily by pace mapping. These linear lesions typically extended from the most abnormal myocardium, with a signal amplitude <0.5 mV, through abnormal endocardium with a good pace map match to annular/valvular structures as previously described.9,12 In patients with less extensive perivalvular bipolar voltage abnormalities, the linear lesion extended across the entire segment of abnormal myocardium.9 More than 1 ablation procedure was required in 13 patients. In 10 patients, a cooled-tip catheter was used for making linear lesions in conjunction with simultaneous CARTO-guided catheter mapping to facilitate accurate cooled-tip catheter lesion localization.

All VTs were seen to originate from endocardium demonstrating abnormal bipolar electrograms, and 52 of the 66 LBBB VTs were localized within 2 to 3 cm of the valve orifice in the RV (Figure 6). Only when the abnormal endocardial electrograms extended for a considerable distance from the valve (10 of the 21 patients) was the LBBB VT site of origin identified in proximity to the apical extent of the identified abnormal endocardium. All 5 VTs with an RBBB morphology had positive R waves from V₁ to V₆ on the 12-lead ECG and were localized to the very basal LV segment in proximity to the mitral valve (Figure 6) from areas demonstrating abnormal bipolar electrograms. At the end of the ablation procedure, 14 of the 19 patients had no inducible VT, and 5 of the patients had polymorphic VT or rapid VT, cycle length <300 ms, that were not targeted for additional ablation. No complications were observed related to the ablation procedure.

Seventeen of the 19 patients (84%) had no VT after ablation during a mean follow-up of 27±22 months (range, 2
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Comparison With Previous Reports Using
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tomy of RV cardiomyopathy and VT and RV

1. Both patients demonstrated mitral and tricuspid perivalvu-
lar contiguous areas of bipolar low-voltage electrogram
abnormalities.
2. RBBB VTs were localized to and ablated in the region of the
mitral valve in both patients.
3. LBBB VTs were localized to and ablated in the region of the
tricuspid valve in both patients.
4. Epicardial mapping was performed in 1 of the 2 patients
and identified low-voltage signals over the basal RV and
LV, with the most marked abnormalities seen in proximity
to the region of the tricuspid and pulmonic valves (Figure 7).
5. Analysis of the explanted heart in the second of the 2
patients identified endocardial fibrosis that corresponded in
distribution to the areas with endocardial bipolar voltage
abnormalities identified during electroanatomic mapping
(Figure 8).

Discussion
The present study provides a detailed clinical and electroana-
tomic characterization and the outcome of catheter ablative
therapy for a consecutive series of patients with VT in the
setting of RV cardiomyopathy. The endocardial bipolar voltage
abnormalities tend to be perivalvular and, although
affecting predominantly the RV free wall, involve some
aspect of the septum in most patients (76%) and uniformly
spare the RV apex. Perivalvular LV endocardial involvement
is common and may be associated with the origin of addi-
tional VT from that chamber. The electroanatomic findings
and the absence of an associated family history in our patients
are most consistent with a fibrotic reaction that extends from
the perivalvular region and perhaps are linked to resolving
inflammation and, less likely, a genetically determined dys-
plastic process. Postinflammatory fibrosis as the pathogenic
mechanism of RV cardiomyopathy and ventricular arrhyth-
rias has been suggested previously and is supported by our
observations.6–8 Finally, the study identifies important anato-
ic landmarks for performing more detailed mapping and
applying a curative ablative strategy in this setting.

Comparison With Previous Reports Using
Electroanatomic Mapping
Boulos et al15 identified areas of low electrogram voltage
involving primarily the RV free wall in 7 patients with
ARVD. Two of the study patients were brothers, but no other
family history was identified. In that report, the authors noted
anterolateral RV involvement in 6 patients, RV outflow tract
involvement in 4 patients, and identified apical involvement
in only 2 patients (28%). They suggested that electrogram
voltage changes should be considered diagnostic for the
disease and an important part of a patient’s evaluation. The
bipolar voltage map abnormalities noted for our study group
of 21 patients extends Boulos’ work and identifies perival-
vular involvement as being uniformly observed. Although
free wall involvement extending from these perivalvular
abnormalities predominates, the septum is more frequently
involved than previously noted. The very apical region of the
RV was noted to be spared in our patients, suggesting that
apical bipolar voltage changes are unusual unless as an
extension of anterolateral involvement. Importantly, only in
that setting was a VT site of origin noted that more closely
approximated the apex.

Pathological Considerations and Relationship to
LV Cardiomyopathy
The disease has been reported to begin epicardially and
progress to the endocardium.6,7,16 Endocardial fibrosis as
reflected by the voltage map findings might be a manifesta-
tion of more extensive disease involvement and might be
anticipated to be the more common substrate for uniform
sustained VT. Consistent with our observations, one report
described diffuse or patchy RV endocardial fibrosis in 14 of
34 hearts (41%) evaluated in an autopsy series of patients
who presented with sudden death.16 Additional study will be
required to determine whether an extensive perivalvular
fibrotic process is fairly specific for patients who present with
sustained unimorphic ventricular tachycardia in the setting of
RV cardiomyopathy.6,7,16 Importantly, previous pathological
studies also documented (1) a high incidence of LV involve-
ment in patients presenting with RV cardiomyopathy, with
LV involvement characteristically basal and lateral in origin,
and (2) a high prevalence (~67%) of inflammatory infl-
Nevertheless, the markedly low epicardial bipolar voltage strongly suggests a process that mimics the endocardial perivalvular changes.

In conclusion, monomorphic VT in the setting of RV cardiomyopathy is associated with a predominantly perivalvular distribution of endocardial electrogram abnormalities and arrhythmia origin that mimics observations made in LV cardiomyopathy and suggests a common pathogenic link. Ablative therapy guided by the electroanatomic data using linear ablation lesions and irrigated-tip catheters facilitates long-term VT control.

References
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*Circulation.* 2004;110:2293-2298; originally published online October 11, 2004; doi: 10.1161/01.CIR.0000145154.02436.90
*Circulation* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2004 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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