EXPRESS PUBLICATION

Mode of Initiation and Ablation of Ventricular Fibrillation Storms in Patients With Ischemic Cardiomyopathy

Nassir F. Marrouche, MD, Atul Verma, MD, Oussama Wazni, MD, Robert Schweikert, MD, David O. Martin, MD, Walid Saliba, MD, Fethi Kilicaslan, MD, Jennifer Cummings, MD, J. David Burkhardt, MD, Mandeep Bhargava, MD, Dianna Bash, RN, Johannes Brachmann, MD, Jens Guenther, MD, Steven Hao, MD, Salwa Beheiry, RN, Antonio Rossillo, MD, Antonio Raviele, MD, Sakis Themistoclakis, MD, Andrea Natale, MD

Cleveland, Ohio

OBJECTIVES
We report on the initiation of ventricular fibrillation (VF) storm in patients with ischemic cardiomyopathy (ICM) and the results of targeted ablation to treat VF storm.

BACKGROUND
Monomorphic premature ventricular contractions (PVCs) have been shown to initiate VF in patients without structural heart disease.

METHODS
A total of 29 patients with ICM and documented VF initiation were identified. In 21 patients, VF storm was controlled with antiarrhythmic drugs and/or treatment of heart failure. Eight patients with VF (mean 52 ± 25 episodes) refractory to medical management required ablation. All patients underwent three-dimensional electroanatomical mapping using CARTO (Biosense-Webster Inc., Diamond Bar, California), and PVCs were mapped when present. Scarred areas were identified using voltage mapping.

RESULTS
Monomorphic PVCs initiated VF in all 29 identified patients. Five of eight patients requiring ablation had frequent PVCs that allowed PVC mapping. The earliest activation site was consistently located in the scar border zone. The PVCs were always preceded by a Purkinje-like potential (PLP). Ablation was successfully performed at these sites. In three patients, infrequent PVCs prevented mapping, but PLPs were recorded around the scar border. Ablation targeting these potentials along the scar border was successfully performed. During follow-up (10 ± 6 months), one patient had a single VF episode and another developed sustained, monomorphic ventricular tachycardia. There was no recurrence of VF storm.

CONCLUSIONS
Ventricular fibrillation in ICM is triggered by monomorphic PVCs originating from the scar border zone with preceding PLPs; targeting these PVCs may prevent VF recurrence. In the absence of PVCs, both substrate mapping and ablation appear to be equally effective.

Patients with ischemic cardiomyopathy (ICM) have an increased risk of life-threatening arrhythmia, including ventricular tachycardia (VT) and ventricular fibrillation (VF). Furthermore, frequent episodes of VF may predict a higher risk of mortality despite the presence of an implantable cardioverter-defibrillator (ICD) (1). Recently, the Purkinje system and premature ventricular contractions (PVCs) have been shown to be responsible for the initiation of VF in patients with no structural heart disease (2–4). A similar mechanism has also been reported in four patients with electrical storm early post-myocardial infarction (MI) (5), but it is still unknown whether this is a consistent mechanism in patients with ICM. The present multicenter study reports on the mode of initiation of VF storm in 29 patients with remote MI and ICM and the use of catheter ablation in 8 of these patients to treat refractory VF storm.

METHODS
Patients. Between January 2001 and June 2003 in four participating institutions, we sought to collect information on and document the mode of initiation of VF storm in patients with ICM. The ethics review boards at all four institutions approved the study. We only included patients with remote MI (>6 months ago) and cases for which the initiation of VF storm was clearly documented on Holter or telemetry monitoring. Patients with torsade de pointes with long-short coupling initiation, acute coronary syndromes, and/or drug-induced pro-arrhythmia were not included in the collection. All patients were initially managed medically, including antiarrhythmic drug therapy, management of heart failure, and correction of electrolytes if necessary.

Mapping and ablation. For those patients refractory to medical stabilization and who had triggering PVCs before their VF, electrophysiologic mapping and catheter ablation was attempted. Multipolar catheters were positioned from the femoral veins into the right ventricular apex and/or right atrium. Access to the left ventricle was via a retrograde...
aortic approach. The left ventricle was mapped using a 7-F 4-mm tip catheter (Navistar, Biosense-Webster Inc., Diamond Bar, California). Surface electrocardiographic leads and bipolar intracardiac electrograms were recorded and filtered at 30 to 400 Hz (Prucka Inc., Milwaukee, Wisconsin). Patients were heparinized to maintain an activated clotting time of 300 to 400 s during left-sided mapping.

In patients with frequent PVCs resembling the PVC morphology that initiated their electrical storm, three-dimensional activation mapping of the PVC was performed using CARTO (Biosense-Webster Inc.). If no spontaneous PVCs were detected, an isoproterenol infusion (up to 6 μg/min) was used to induce more PVCs. Based on previously published data in normal hearts, careful attention was made to identify any low-amplitude, high-frequency, Purkinje-like potentials (PLPs) preceding the PVCs at the earliest activation sites of the PVC. The simultaneous voltage map was used to identify infarct-related scar and to define the scar border zone. Scar tissue was defined as a local voltage of <0.5 mV and normal tissue as >1.5 mV.

In patients in whom PVCs could not be detected in sufficient quantity to permit PVC mapping, sinus rhythm substrate mapping was performed using CARTO (Biosense-Webster Inc.). Scar and scar border zones were defined as previously mentioned. Based on previous data demonstrating the pro-arrhythmic nature of the scar border zone (6) and our own early experience with the location of PVCs in the first three patients of this series, careful mapping along the border zone was performed to identify similar low-amplitude, high-frequency PLPs previously mentioned.

Radiofrequency (RF) ablation was performed in all patients with a cooled-tip ablation catheter (Navistar, Biosense-Webster Inc.). This catheter was used to allow higher power delivery to a maximum of 60 W and temperature of 55°C. The RF current was applied for a maximum of 120 s at a time. For patients with inducible PVCs, the earliest activation site of the PVC was targeted. Ablation was considered acutely successful if no PVCs could be documented 30 min after the last RF lesion. If PVCs recurred, more RF lesions were applied in the target region. For those patients without inducible PVCs, ablation was performed along the scar border zone in locations where the PLPs were identified. The end point was application of scar border zone lesions until all PLPs were abolished.

Follow-up. Post-ablation patients were followed at 1, 3, 6, and 12 months. Patients with ICDs had interrogation at each follow-up for detection of non-sustained/asymptomatic ventricular arrhythmias. One patient remained hospitalized post-ablation awaiting cardiac transplantation on telemetry. Recurrence was defined by patient symptoms, ICD shocks, and/or detection of ventricular dysrhythmias on device interrogation.

Data. All data are presented as a mean ± standard deviation.

RESULTS

Mode of initiation of VF storm. A total of 29 patients with VF storm were identified who met the inclusion criteria. All patients had ICM with an average ejection fraction of 17 ± 4%. Additionally, 28 of 29 patients had ICDs; 8 (27%) patients presented with electrical storm in the setting of decompensated heart failure, and 5 (17%) patients presented post-open heart surgery. The remaining patients (n = 16) presented with "spontaneous" electrical storm without any clear precipitant. None of the patients had acute, ischemic electrocardiographic changes, significant elevations in cardiac enzymes, or new severe coronary artery lesions.

The mean number of VF episodes over 24 h was 7.5 ± 3.0. In the majority of patients (21 of 29), electrical storm was stabilized with treatment of decompensated heart failure (n = 5), or antiarrhythmic drug therapy (n = 16; 15 on amiodarone, 1 on dofetilide). In the eight remaining patients, VF storm was refractory to medical therapy, with seven patients having ongoing ICD discharges and one patient having multiple arrests with hemodynamic compromise despite the presence of a left ventricular assist device (LVAD).

In all 29 patients, VF storm was observed to initiate with a monomorphic PVC (Figs. 1A and 1B). The PVC had a right bundle-branch block pattern in all cases, with a mean QRS duration of 178 ± 25 ms. Five of the beats had a superior axis and 24 had an inferior axis. The mean coupling interval of the PVC was 195 ± 45 ms.

Ablation of VF storm. The eight patients who had refractory VF storm underwent electrophysiologic mapping and ablation. Baseline characteristics of these patients are detailed in Table 1.

Table 2 shows the mapping, ablation, and follow-up results for the patients who underwent ablation. Four of eight patients presented to the laboratory with frequent, spontaneous monomorphic PVCs, which triggered episodes of non-sustained polymorphic VT. In one of eight patients, isoproterenol at 3 μg/min was needed to reproduce the clinical PVC in sufficient quantity to allow mapping. In the remaining three patients, no PVCs were induced and sinus rhythm mapping was performed.

In the five patients with spontaneous PVCs, mapping of the monomorphic PVC was performed. In all five cases, the clinical PVC was preceded by a low-amplitude, high-
frequency potential resembling a PLP (Fig. 1C). The potential preceded the PVC by a mean of 68 ± 20 ms (Table 1) with a fixed coupling interval. In all five patients, the earliest site of activation of the PVC was localized within the border zone of the ischemic scar (Fig. 2). Ablation was performed in this region in all five patients. Acutely, no PVCs were detected post-ablation. However, in two patients, additional, fast, monomorphic VT (not VF) was induced by programmed ventricular stimulation. These VTs were mapped and ablated. In both cases, several RF lesions along the scar border zone had to be applied to eliminate the induced VT. No VT or PVCs were induced after this procedure.

Based on the early observation from three of five of the above patients that the triggering PVC was consistently localized to the scar border zone, mapping for PLPs and ablation was performed on this zone in the remaining three patients in whom spontaneous PVCs could not be induced. In all three patients, low-amplitude, high-frequency potentials similar to those preceding target PVCs were observed during sinus rhythm along the scar border zone (Fig. 1C). Ablation lesions were applied all along the length of the scar border zone.}

**Figure 1.** Panels A and B depict electrocardiographic (ECG) strips from one ventricular fibrillation (VF) storm patient who underwent ablation. Panel A shows a monomorphic premature ventricular contraction (PVC) (*) initiating non-sustained polymorphic ventricular tachycardia. Panel B shows the same morphology PVC (*) initiating VF. Panel C depicts surface ECG (I, II, III, AVR, AVL, AVF, V1, V2, V3, V4, V5, V6) and intracardiac recordings from the ablation catheter (ABLp). The vertical caliper lines on the third beat of the tracing (†) indicate a high frequency potential preceding the PVC by 70 ms. Similar high-frequency Purkinje-like potentials are also seen during the two sinus beats that precede the PVC (arrows).
border zone in order to eliminate all detected potentials. After the procedure, a fast, monomorphic VT was induced in one patient, but no further ablation was performed because of hemodynamic instability during VT.

**Follow-up.** The VF storm acutely subsided in all eight patients post-ablation. At a mean follow-up time of 10 ± 6 months, only one patient (the one with an LVAD) experienced a single episode of VF. Another patient developed a slow, monomorphic VT (cycle length 580 ms), which resulted in a single ICD shock over 11 months. It was hemodynamically stable and successfully ablated. In three patients, non-sustained episodes of monomorphic VT were documented through ICD interrogation, but none resulted in any ICD therapy.

None of the eight patients died during follow-up of either arrhythmia or heart failure. One death occurred during follow-up in the LVAD patient secondary to septic shock.

**DISCUSSION**

The primary findings of our study are that: 1) even in the presence of ICM, VF storm is frequently initiated by monomorphic PVCs; 2) these triggering PVCs appear to be related to PLPs originating from the scar border zone; and 3) ablation of these PVCs and/or potentials in the border zone region can control VF storm. All patients at post-ablation were free of VF storm and free of arrhythmia over a relatively long follow-up, or they experienced only a sporadic event. This is the first report to describe initiation and ablation of VF storm in patients very remote from MI. This is also the first report to suggest that empiric ablation of PLPs in the scar border zone without inducible PVCs can also successfully control VF storm.

Our results are consistent with other studies that have demonstrated that VF is initiated by PVCs in normal hearts, and that ablation of these PVCs may prevent VF (2,3). Our findings also agree with a recent report of four patients with electrical storm early post-MI triggered by PVCs and controlled by PVC ablation (5). Although others have suggested the scar border zone as the principal source of triggering potentials (5,7), our study emphasizes this point by demonstrating that empiric ablation of PLPs along the border zone successfully controls VF storm. Data from animal models have also long demonstrated the border zone as an important site of triggered PVCs and ventricular dysrhythmias (8,9). Thus, our anatomical approach targeting the border zone may be promising in the treatment of VF in ICM, but it requires further validation. Definition of the border zone may be difficult in patients with extensive scar, but we did not find that this limited us, even in the LVAD patient. Furthermore, a similar procedure has been successfully reported for treatment of hemodynamically unstable VT (10).

Whether eliminating all potential triggers along the border zone is superior to targeting a single PVC is unclear and warrants further study. In all 29 cases of our report, a monomorphic PVC was responsible for triggering VF, suggesting that focused ablation of this PVC (when possible) should be sufficient.

Our finding that PVCs were consistently preceded by low-amplitude, high-frequency PLPs supports the hypothesis that triggered activity from these fibers is responsible for the PVCs that initiate VF (4). In animal models, triggered activity from surviving distal Purkinje arborizations in the scar border is required for the development of VF (11). However, triggered activity can also result via electrotonic interactions between ischemic and normal myocardial cells (8). Micro-re-entry could also cause PVCs, because co-existing scar and viable myocardium create opportunities for

---

**Table 1.** Baseline Characteristics of Patients Undergoing Ablation

<table>
<thead>
<tr>
<th>Age (yrs)</th>
<th>Gender (male)</th>
<th>Ejection fraction (%)</th>
<th>Implantable defibrillator</th>
<th>Left ventricular assist device*</th>
<th>Revascularization in last 6 months</th>
<th>Time since last myocardial infarct (months)</th>
<th>Mean number of VF episodes at presentation</th>
<th>Time from initial VF to ablation (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 ± 8</td>
<td>6/8</td>
<td>15 ± 4</td>
<td>7/8</td>
<td>1/8</td>
<td>6/8</td>
<td>11 ± 5</td>
<td>52 ± 25 (range 35–89)</td>
<td>14 ± 20</td>
</tr>
</tbody>
</table>

*Implanted for refractory heart failure and as bridge to transplantation.

VF = ventricular fibrillation.

---

**Table 2.** Mapping and Follow-Up Data of Patients Undergoing VF Storm Ablation

<table>
<thead>
<tr>
<th>Patient #</th>
<th>Scar Location</th>
<th>Territory of Remote MI</th>
<th>PLP-PVC (ms)</th>
<th>Recurrence of VF</th>
<th>Recurrence of VT</th>
<th>ICD Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Anteroseptal</td>
<td>LAD</td>
<td>70</td>
<td>No</td>
<td>Sustained</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Anteroseptal</td>
<td>LAD</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Posteroseptal</td>
<td>RCA</td>
<td>N/A</td>
<td>No</td>
<td>Non-sustained</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Posteroseptal</td>
<td>RCA</td>
<td>38</td>
<td>No</td>
<td>Non-sustained</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Anterolateral</td>
<td>LAD</td>
<td>76</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Anteroseptal</td>
<td>LAD</td>
<td>N/A</td>
<td>No</td>
<td>Non-sustained</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Anterolateral</td>
<td>LAD</td>
<td>48</td>
<td>No</td>
<td>Non-sustained</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>Lateral</td>
<td>Cx</td>
<td>88</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Cx = circumflex artery; ICD = implantable cardioverter-defibrillator; LAD = left anterior descending; MI = myocardial infarction; N/A = not applicable; PLP-PVC = duration from Purkinje-like potential to premature ventricular contraction; RCA = right coronary artery; VF = ventricular fibrillation.
electrical re-entry (6). The PLPs we observed could represent diastolic potentials in a re-entrant circuit, but those are usually more fractionated and a much lower frequency than the potentials described in this report.

An important clinical finding was that most of the 29 patients initially identified responded to medical management of VF storm (n/H1100521). Therefore, ablation is a therapy best reserved to that small proportion of patients who fail medical management.

**Study limitations.** The observation that PVCs triggered VF storm in all 29 patients reported suggests that this mechanism may be responsible for a significant proportion of VF storm, but not necessarily all VF storm. We cannot quantify the proportion as our study selected only those patients who survived long enough to present to the hospital and have their episodes documented. We also cannot rule out that in the eight patients undergoing ablation, arrhythmia subsided as part of the natural history of electrical storm (12) rather than due to ablation. This is unlikely, however, given the frequent and resistant nature of the VF episodes; it would have been very coincidental that storm subsided immediately post-ablation in all eight patients. Finally, given our limited follow-up duration, we cannot draw any conclusions as to whether ablation for VF in ICM provides any long-term or mortality benefit.

**Conclusions.** The VF storm in patients with ICM seems to be triggered by monomorphic premature ventricular beats, which appear to be driven by Purkinje-like triggered activity originating from the scar border zone. Ablation of these triggers may be performed safely and may prevent recurrence of future VF. Furthermore, substrate-mapping that targets PLPs along the scar may be a suitable and equally effective alternative approach in patients who have no premature beats at the time of ablation.

**REFERENCES**


**Reprint requests and correspondence:** Dr. Andrea Natale, Co-Section Head of Pacing and Electrophysiology, Director Electrophysiology Laboratory, Co-Chairman Center for Atrial Fibrillation, Cleveland Clinic Foundation, 9500 Euclid Avenue, Desk F 15, Cleveland, Ohio 44195. E-mail: natalea@ccf.org.

**Figure 2.** Three-dimensional voltage CARTO (Biosense-Webster Inc.) map of the left ventricle in a patient who underwent ablation for ventricular fibrillation storm and also had a left ventricular assist device (LVAD). Red regions on the map represent scar, whereas green and blue regions represent abnormal tissue in the scar border zone. Purple indicates normal voltage >1.5 mV. The red circle indicates the site where premature ventricular contractions preceded by high frequency Purkinje-like potentials were mapped and successfully ablated. The ablation site is located along the edge of the scar region in the border zone. MA = mitral annulus.