Entrainment/Mapping Criteria for the Prediction of Termination of Ventricular Tachycardia by Single Radiofrequency Lesion in Patients With Coronary Artery Disease

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Background—A variety of mapping criteria have been proposed to localize critical sites at which radiofrequency (RF) can predictably terminate reentrant ventricular tachycardia (VT) caused by coronary artery disease. The purpose of this study was to determine the accuracy of using a combination of 3 mapping criteria in predicting termination of VT by a single RF lesion.

Methods and Results—Fifteen consecutive patients with coronary artery disease and recurrent sustained VT underwent an attempted RF ablation of 20 monomorphic VTs. Successful termination of VT by a single RF lesion was predicted if all the following mapping criteria were met: (1) an exact QRS match in the 12-lead ECG during entrainment; (2) a return cycle length $\leq 10$ ms of the VT cycle length; (3) presystolic potentials ($<70\%$ of VT cycle length) with an activation time to the QRS within 10 ms of the stimulus to QRS. Inability to meet these 3 criteria was considered to predict failure of VT termination by RF energy at that site. RF ablation was applied to 44 left ventricular sites in 20 VTs at which at least 1 of the mapping criteria was met. VT was terminated with a single RF lesion in 19 of 19 sites meeting all criteria; RF failed to terminate VT at 24 of 25 sites at which all 3 criteria were not met ($P<0.0005$).

Conclusions—To maximize success and minimize the number of RF lesions in patients with infarct-related VT, all the above 3 mapping criteria should be met before the application of RF energy. (Circulation. 1999;99:2283-2289.)

Key Words: catheter ablation ■ tachycardia ■ mapping ■ coronary artery disease

In recent years, radiofrequency (RF) catheter ablation has become widely accepted as a highly effective and safe therapeutic modality in the treatment of supraventricular tachyarrhythmias and ventricular tachycardias (VT) in the absence of structural heart disease. There has been variable success in the application of RF ablation in patients with infarct scar–related VT.1–4 The variable success has been attributed to multiple reasons including (1) inaccurate mapping due to failure to apply appropriate criteria for localizing a protected isthmus and/or inability to find such a site2–8 and (2) inadequate lesion size produced by RF.9,10 Multiple criteria have been used to guide VT ablation including pace mapping, S-QRS time, presystolic electrogram, and concealed entrainment with return cycle equal to VT cycle length (CL).4–7,11–16 No set of criteria has been proposed to increase the positive prediction of termination of VT with a single RF application. Such criteria, if attainable, would decrease the chance to apply RF applications to noncritical areas, for example, protected loops or dead end pathways. We hypothesize that the use of the following 3 criteria in combination will identify the critical isthmus in VT, exclude other noncritical areas in or outside of the VT circuit, and increase the likelihood of termination of the VT with single RF application at a single site. These criteria include (1) exact 12-lead QRS match during concealed entrainment; (2) return CL within 10 ms of VT CL; and (3) presystolic potentials ($<70\%$ VT CL) with activation time to QRS within 10 ms stimulus to QRS.

Methods

Patient Characteristics

Fifteen consecutive patients with coronary artery disease and drug-refractory, recurrent, hemodynamically stable sustained monomorphic ventricular tachycardia were referred for RF ablation of VT at the Beth Israel Hospital, Boston, between January 1993 and December 1996. There were 12 men and 3 women. The mean patient age was $71\pm10.9$ years ($\pm$ SD). All the patients had at least 1 prior infarction (4 anterior, 6 inferior, and 5 both anterior and inferior). Their mean left ventricular ejection fraction was $25.6\pm8.6\%$. At the
time of the ablation procedure, 7 patients were being treated with antiarrhythmic agents (5 with amiodarone, 1 with procainamide, and 1 with amiodarone and disopyramide). Two patients had undergone implantation of an internal cardioverter-defibrillator (ICD) before the ablation procedure and experienced multiple ICD shocks for the termination of VT.

Protocol

Electrophysiological procedures were performed with the subjects in the fasting state after informed consent was obtained. Quadripolar catheters (6F) were inserted percutaneously through the femoral veins into the right ventricular apex and right ventricular outflow tract. A quadripolar 4-mm deflectable-tip mapping catheter with a thermistor for monitoring temperature at the electrode tissue interface was inserted into the left ventricle retrogradely through the femoral artery. A bolus of 5000 U of heparin followed by an infusion of 1000 U per hour was given before entry into the left ventricle. Programmed ventricular stimulation was performed with a programmable stimulator (Bloom Associates LTD) with the use of a current strength twice the diastolic threshold. The intracardiac electrograms and leads I, II, aVF, V₁, and V₅ were displayed on an oscilloscope and digitally recorded on optical disk by Cardio Laboratory system (Prucka Engineering). Bipolar intracardiac electrograms recorded from the distal and proximal electrode pair of the mapping catheter were filtered at 30 to 500 Hz. Right ventricular stimulation with up to 3 ventricular extrastimuli using up to 3 basic drive train cycles at the right ventricular apex and outflow tract was used to induce VT. Induced VTs were recorded on a 12-lead ECG. Left ventricular mapping was performed as previously described by Josephson et al.⁶ The mapping catheter had a 4-mm ablation tip with 2–5-2-mm spacing for proximal electrodes. We used poles 1 to 3 (distal) and 2 to 4 (proximal) of the ablation catheter for recording and poles 1 to 3 for stimulation during VT with the lowest current that captured the VT at a CL of 20 to 50 ms less than the VT CL. The pulse width was 2 ms in duration. Catheter position was identified fluoroscopically in the right and left oblique positions. PACing was done at selected left ventricular sites during VT, all of which exhibited presystolic endocardial activation preceding the onset of the QRS by ≥50 ms during VT, with the use of stimuli that captured the ventricle with the least current as described above. Activation times were taken from the onset of the electrogram. Twelve-lead ECGs during pacing and VT were compared to evaluate if entrainment with fusion or concealed entrainment was present. The return cycle (measured from the stimulus to onset of the presystolic electrogram of the first unpaced beat), local electrogram to QRS interval, stimulus to QRS interval, and VT CL before pacing were measured on the distal pole recording, preventing reliable measurement. The proximal pair was always the same as that recorded during the native tachycardia and was virtually indistinguishable from the distal pair. We used right ventricular electrograms as an additional reference to measure return cycles (right ventricular return cycle should equal left ventricular return cycle) and the relation between the left ventricular site and the right ventricle (left ventricular to right ventricular interval during pacing should equal that during VT). The return cycle was defined as the interval from the last paced beat to the first VT beat (measured from the stimulus to onset of distal or proximal left ventricular electrogram). Entrainment of VT with fusion was defined as continuous resetting of VT with constant QRS fusion. Entrainment of VT with concealed fusion was defined as continuous resetting of VT by stimuli that did not alter the QRS configuration. An exact 12-lead QRS match was defined as identical QRS morphology, amplitude, slurring, and notching during pacing to the QRS of the VT (Figure 1). The following 3 criteria were used to predict success or failure of RF in termination of VT: (1) exact 12-lead QRS match during concealed entrainment; (2) return CL within ±10 ms of the VT CL with the use of both the distal and/or the proximal electrodes on the ablation catheter and 1 or more right ventricular reference electrograms; and (3) presystolic potentials (70% VT CL)
with local activation time (electrogram) to QRS within ±10 ms stimulus to QRS.

Stimulation was only performed at sites in which diastolic electrograms were recorded in regions, based on VT ECG morphology, suggested a possible site of origin. Before delivering a lesion, the 12-lead ECG during entrainment and intracardiac electrograms were reviewed and a prediction of the response to the RF lesion was noted. If the 3 criteria were fully met (Figure 2), application of RF at this site was predicted to be successful (Figure 3). If only 1 or 2 criteria were met, application of RF at this site was predicted to be a failure. Once a target was selected, RF energy was delivered as a continuous, unmodulated sine wave 500 kHz between the distal electrode of the ablation catheter and a large skin electrode on the posterior chest. Applications of RF energy were delivered during VT at a power of 30 to 50 W with non–temperature-controlled catheters and a target temperature of 65°C (range 60 to 70) when temperature-controlled catheters were used. All lesions were delivered for at least 1 minute unless a rise in impedance was noted. If the VT terminated during RF application, the energy application was continued for a total of 120 seconds. In the event of an impedance rise, the ablation catheter was removed from the body and the distal electrode was wiped clean of the coagulum before continuing with the procedure.

Programmed stimulation for induction of VT was repeated after successful termination of VT by RF application either at the end of the study or in a repeat study before hospital discharge 2 to 4 days after the initial application in all patients except 2 who refused. Induced nonclinical VT were not targeted if they were the only induced tachycardias after the initial ablation. Another objective of the study was to evaluate the clinical significance of these induced tachycardias. Two of the nonclinical tachycardias underwent attempted ablation (1 successful) because they were in immediate proximity (on the basis of ECG monitoring and activation mapping) to the clinical VT.

Clinical Follow-Up Data

The patients were followed at our arrhythmia clinic periodically every 3 to 6 months for clinical recurrences. The mean follow-up was 15 months (range 3 to 36 months).

Statistical Analysis

Values are expressed as mean ± 1 SD. Comparisons were performed with the use of Student’s t test and Fisher exact test. A probability value of <0.05 was considered significant. Positive predictive value was defined as true-positives / (true-positives + false-positives), and the negative predictive value was defined as true-negatives / (true-negatives + false-negatives).

Results

VT mapping and ablation was attempted in 20 sustained monomorphic VTs, 18 of which were documented clinically and 2 of which were induced but not documented. Ablation of these 2 nondocumented VTs was attempted due to their immediate proximity to the clinical VTs. An additional 15 stable monomorphic VTs that had not been documented to occur spontaneously were induced, but ablation was not attempted. There were 13 right bundle-branch block VT and 7 left bundle-branch block VT. The mean VT CL was 367 ± 88 ms (range 290 to 590). Seven of the 15 patients received intravenous procainamide during ablation to increase the CL of the VT. RF applications were applied to a total of 44 sites in 20 induced monomorphic sustained VTs. RF at each site was predicted for either success or failure after entrainment/mapping was performed. Nineteen of the 20 VTs had sites that met all 3 criteria. In 1 VT, no site met all criteria. Nineteen of 20 VTs were successfully terminated with single RF application delivered at sites that met the 3 mapping criteria. Thus RF application at 19 of 19 sites meeting all 3 criteria terminated VT. In 2 of these 19 VTs, the VT continued to be inducible after successful termination with single RF application at sites in which all 3 entrainment/mapping criteria were met. Further applications of RF applications at the site meeting all 3 criteria resulted in termination and noninducibility of 1 VT, but 1 clinical VT continued to be inducible despite reproducible termination at the site that predicted termination. During this VT, RF applications were
Figure 3. Successful ablation at site has all 3 criteria A, Intracardiac recording during entrainment demonstrating all 3 criteria. B, Successful ablation at this site.
delivered, predicted to fail at 2 sites, and failed. There were 25 sites at which only 1 or 2 of the entrainment criteria were met. RF application failed to terminate VT in 24 of 25 applications at these sites. Of the 25 sites not meeting all 3 criteria, the most common findings were (1) stimulus to QRS > electrogram to QRS and return cycle > VT cycle (8 sites). This suggested a dead end pathway attached to the isthmus. (2) QRS fusion but return cycle = VT cycle and stimulus to QRS = electrogram to QRS. This suggested the site was in the circuit but not in the isthmus (7 sites). (3) Four sites had stimulus to QRS > 70% VT cycle length. (4) QRS fusion with return cycle > VT CL suggesting a site outside the circuit (4 sites). (5) Two sites exhibited inner loops characteristics.

Successful termination of VT occurred in the first 10 seconds of the application of RF energy in 75% of VTs; 95% were terminated within 32 seconds. Nineteen of the 20 targeted VTs were terminated with an RF application at a single site. Eighteen of these were the clinically documented VT and 1 was a nonclinical (ie, induced but never before seen) VT. After RF ablation, all but 2 patients underwent ventricular stimulation. Only 1 clinical VT continued to remain inducible in a patient in whom the VT was reproducibly terminated at a site meeting all 3 criteria. The positive predictive value of these strict mapping criteria to predict VT termination with RF application at that site was 100%, whereas their negative predictive value was 96%. The sensitivity of these criteria was 94%; specificity was 100%.

Follow-Up
Patients were followed for a mean of 15 ± 8.8 months. One patient died from multiple cardiovascular accidents and recurrent myocardial infarction 27 months after the ablation without evidence of recurrent VT. 1 patient who had failure of VT ablation (reproducible termination of VT by RF but persistently inducible) died 6 months later from progressive heart failure (no clinical VT recurrence), and 1 patient died 3 years after VT ablation as the result of progressive neurologic disease (amyotrophic lateral sclerosis). Two patients received an ICD after VT ablation because the referring physician wanted therapy for inducible multiple nonclinical VTs. There was no evidence of recurrence of ablated VT. Four patients had recurrences of VT. In each instance it was a stable VT inducible at electrophysiologic study but not targeted for ablation. Electrocardiograms of the spontaneous VTs in 2 patients without ICDs documented the QRS morphology. Both of these patients underwent a second successful ablation. The 2 other VT recurrences were in patients with ICDs. The electrograms and CL of VTs in this ICD was successful in both patients, therefore no further attempts at ablation were made. All patients (5) receiving a stable dose of the antiarrhythmic medication remained free of recurrence of ablated VT. Three patients were discharged receiving no medication, without evidence of recurrence of VT.

Discussion
Results of ablation of the infarct-related VT has been improving over the last 10 years with our better understanding and better selection of ablation sites. Initial attempts at ablation targeted early presystolic potentials; this was followed by use of mid-diastolic potentials. Both electrograms led to unsatisfactory results. Presystolic potentials were found to be nonspecific, as they might be in an area at the scar tissue, for example, inner loop, bystander (inner sites attached to the central pathway), or not related to the VT circuit. Mid-diastolic potentials, which cannot be dissociated from the VT during entrainment, are uncommon (30% of patients) and could be at a bystander site. Demonstration of concealed entrainment of VT as a guide to VT ablation has increased over the last few years. However, concealed entrainment alone to guide VT ablation, without multiple other criteria, has only 50% positive predictive value for terminating VT. The use of multiple criteria (eg, stimulus to QRS prolongation, mid-diastolic potentials) have been suggested either alone or in combination to improve identification of the critical zone of the VT. These criteria have a different sensitivity and specificity with variable positive predictive values whenever used in different combinations. Thus we prospectively tested a specific set of criteria to optimize better site selection and a predictable high success rate. Our 3 criteria included (1) exact 12-lead QRS match during concealed entrainment; (2) return CL within ± 10 ms of the VT CL with the use of both distal and/or proximal electrodes on the ablation catheter and 1 or more right ventricular reference electrogams; and (3) presystolic potentials (70% VT CL) with local activation time (electrogram) to QRS within ± 10 ms stimulus to QRS. We were able to locate sites with all 3 suggested criteria in 19 of the 20 attempted VTs (95%). The inability to find the appropriate target site in all cases might be due to multiple reasons, including large amount of scar tissue, intramyocardial or epicardial location of the VT isthmus, or technical difficulty in catheter manipulation. In addition, acceleration, termination, or changing of VT to a different arrhythmia during attempts at entrainment limit the reality of mapping all VT.

In this study, the success rate for termination of VT by single RF application when the 3 criteria were met had a positive predictive value of 100% and negative predictive value of 96%. These results are not in contradiction of any previous studies but propose a more accurate method of selecting a successful site for ablation. The recent study by Bogun et al in 1997 found similar criteria helpful and, if combined, had a positive predictive value of 80% to 90%. Their study was a retrospective evaluation of sites of ablation, and multiple lesions may have been applied in an awe of interest. Thus no true predictable data about mapping accuracy could be gleaned from their report. The total number of VT ablated in this study was small; however, it was representative of the selected group of patients with VT caused by infarct scar. Of the 15 patients included in the present study, there were 2 patients who had ICD implantation before the ablation and 2 who had ICD implantation after the ablation because of induction of fast VT before discharge. There was
no recurrence of the VT during the 15±8.8-month follow-up period.

The use of S-QRS equal to local electrogram to QRS is helpful in excluding sites which are bystanders. Stevenson et al in 1993 suggested from computer simulation analysis that an S-QRS interval >70% of the VT CL is suggestive of a site outside the isthmus. Of interest, Bogun et al did not find return CLs within 30 ms helpful either alone or in combination with the other criteria. Because our study looked prospectively at the use of 3 entrainment/mapping criteria together and required the return CL to be within 10 ms of the VT CL, we found it useful and necessary. Statistically, if during true concealed entrainment the S-QRS was equal to the local electrogram to the QRS and the S-QRS is <70% of the VT CL, there the return CL should equal the VT CL. We found that use of the right ventricular electrogram as a reference was helpful in confirming return cycle measurements, especially in cases in which noise in the recording of the distal electrode during pacing made the local measurements impossible.

Persistence of inducibility of VT after successful termination with single RF application despite further applications of RF energy at the same site is probably due to multiple reasons, for example, wide isthmus, epicardial location, or significant fibrosis and/or calcification.2,17 all of which suggest inadequate lesion size at the cause of failure.

The most interesting issue was the success of termination of VT at a site at which failure was predicted. This could occur if the site was not at the isthmus region but in the nearby vicinity with good conduction of temperature. It is also possible that the tip of the ablation catheter was at the isthmus but during pacing with a high current, a larger area was depolarized, resulting in fusion.

Early studies revealed a recurrence of ablated clinical VT or some of the induced nonclinical VT in up to 30%.13,19 We had no recurrences of ablated VTs or induced poorly tolerated nonclinical VT during follow-up. Our recurrence rate in this study might be affected by the short duration of follow-up or the total number of patients included. Although the natural history of recurrence of induced nonclinical VT was evaluated recently by Rothman and colleagues,5 patient selection may be important. In contrast to Rothman et al, none of our patients had prior ventricular fibrillation or were resuscitated from cardiac arrest. In addition, most of our patients had 1 to 2 spontaneous monomorphic VTs with a mean of 2.3 induced VTs, whereas in the study of Rothman et al5 the mean induced VTs were 5.3±2.7. Tolerated or untolerated nonclinical VTs are not well defined in all prior published studies. The attempt to ablate multiple VTs, especially if they are not anatomically related or share a common isthmus, might be the cause of the difference in these results that is, higher recurrence rate. Also, none of our patients had prior cardiac arrest, and all were maintained on drugs that were used before ablation and made their VT slow and tolerable. Thus our patient population differed from that of Rothman et al in that we had no patients with cardiac arrest and all were maintained on the drugs present at the time of ablation. The goal of this study was to evaluate the success of termination of VT by RF application at a single site, not to establish the long-term recurrence of induced nonclinical VT.

Of note, 75% of ablated VT terminated within 10 seconds of the application of RF and 95% within 32 seconds. Although the total number of ablated VTs is small, successful termination of VT occurs within 30 seconds of RF application. We therefore, suggest discontinuation of RF energy application if there is no termination of VT by 30 seconds in order to decrease the likelihood of ablation of noninvolved myocardial tissue with impairment of left ventricular function.

This is the first study that prospectively tests the predictive accuracy of a specific set of entrainment/mapping criteria for guiding RF ablation of VT. Previous studies comparing the sensitivity and specificity of different entrainment criteria had lower predictive accuracy. Mid-diastolic potentials, which are unable to be dissociated from the tachycardia during pacing, have been used to guide ablation but they are uncommon and may still represent a bystander site attached to the isthmus.

Limitations

Potential limitations of this study are (1) activation times based on bipolar recordings with a 4-mm electrode as the distal electrode, (2) the possibility that RF energy might be delivered distant to the recorded site, particularly using high current, and/or produce damage beyond the recording/stimulation site, and (3) measuring the return CL from the 2 to 4 pole if 1 to 3 pole had interference (although we did validate the measurement by use of a right ventricular electrogram as a reference), (4) bipolar stimulation at relatively high milliampere used during entrainment might result in capturing an area larger than the local area, (5) some of the failed RF lesion might be due to inadequate heating or inadequate lesion size rather than failure to identify the critical zone of the tachycardia, (6) the number of patients selected for this study is small and might not represent the general population with sustained VT.2,5,13,17,19 This study does not address the utility of ablation as primary therapy of VT. A number of factors not addressed in this report are relevant to answering this question, including: access to the left ventricle, ability to induce VT, and the ability to completely map VTs. Nevertheless, the use of these criteria results in successful termination and potential “cure” of VT. Further studies are necessary to allow a better understanding of how many lesions are necessary to prevent recurrences or if a single larger lesion, such a produced by a cool-tip catheter, would suffice if rigorous mapping criteria were followed. While a prospective randomized trial of RF attempts at sites meeting 1, 2, or all 3 criteria might provide a more accurate assessment of true predictive value, the successful termination of all tachycardias meeting these criteria and only 1 of 25 not meeting them suggests these are valuable ablation guides.

Conclusions

Although our data have limitations in terms of patient numbers, the ability to successfully “cure” VT suggests that in appropriate patients, RF ablation can be considered an option as a first line of therapy for stable VT. Achievement of our strict entrainment/mapping criteria is possible in the
majority of clinical VT. To maximize success and minimize the number of RF lesions, all 3 entrainment/mapping criteria should be met before the application of RF energy. No patient had a cardiac arrest or rapid VT during follow-up despite the frequent initiation of untolerated monomorphic and polymorphic VT. The requirement of ablating all induced non-clinical VT (tolerated and untolerated) remains to be established.

References
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