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Mechanism of Ventricular Tachycardia Termination by Pacing at Left Ventricular Sites in Patients with Coronary Artery Disease

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Abstract. ***Objective:*** **The mechanism by which pacing terminates ventricular tachycardia (VT) may depend on the location of the pacing site relative to the reentry circuit. The purpose of this study was to compare the mechanisms by which pacing terminates VT at left ventricular (LV) sites with and without concealed entrainment (CE) in patients with prior myocardial infarction.**

Methods and Results: **LV mapping was performed in 29 patients (26 men, 3 women, mean age 67 ± 11 years, ejection fraction 0.28 ± 0.11) with 55 hemodynamically-tolerated VTs (mean cycle length 478 ± 92 msec). A total of 408 pacing trains were delivered at 102 sites with CE. Radiofrequency catheter ablation was successful in 41 of 55 VT's. At sites with concealed entrainment, VT was terminated by pacing at 17/41 (41%) successful and at 4/61 (7%) unsuccessful ablation sites ($p < 0.01$). Termination without global ventricular capture was the most frequent termination mode (10/21), followed by termination with orthodromic (4/21) and non-orthodromic capture (7/21).**

Conclusion: **In patients with prior myocardial infarction, pacing at sites of CE during VT usually terminates VT either without global capture or by orthodromic capture. Termination of VT by pacing without global capture or with orthodromic capture at sites of CE suggests that the site is within a critical area of the reentry circuit.**

Key Words. **mapping, concealed entrainment, coronary artery disease, pacing, VT ablation**

Introduction

Concealed entrainment identifies zones of slow conduction within ventricular tachycardia (VT) reentry circuits in patients with prior myocardial infarction [1,2]. However, concealed entrainment is not specific to critical sites within the reentry circuit. On the other hand, termination of VT by subthreshold pacing is specific to critical sites within the reentry circuit [3]. The purpose of this study was to determine the prevalence and mechanisms by which pacing at sites of concealed entrainment terminates VT.

Methods

Patient Characteristics

Twenty-nine patients (26 men and 3 women) with a mean age of 67 ± 11 years (±standard deviation) and with coronary artery disease underwent an electrophysiology procedure aimed at radiofrequency ablation of drug-refractory VT. Their mean left ventricular ejection fraction was 0.28 ± 0.11. All patients had a history of at least one myocardial infarction (anterior in 6 patients, inferior in 11 patients, and both anterior and inferior in 12 patients).

A total of 55 VT's with a mean cycle length of 478 ± 92 msec that were hemodynamically-tolerated were mapped for the purpose of radiofrequency catheter ablation. All mapped VT's were sustained and never terminated spontaneously. Twenty-six of the VT's had a left bundle branch block and 29 had a right bundle branch block morphology. The indication for the ablation procedure was incessant VT in 3 patients, frequent internal cardioverter/defibrillator discharges in 15 patients, and recurrent episodes of monomorphic VT resulting in palpitations in 11 patients. All patients had failed antiarrhythmic drug therapy,

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including amiodarone in 17 patients. Twenty-two of the 29 patients also were subjects of a prior report [4].

Electrophysiologic Study and Mapping

After informed consent was obtained, 2 or 3 quadripolar electrode catheters were inserted into a femoral vein and positioned in the right atrium, His bundle position, and right ventricular apex. A 7Fr, quadripolar, temperature-sensing electrode catheter with interelectrode spacing of 2-5-2 mm and a deflectable tip (Webster, Mansfield or EP Technologies) was inserted into a femoral artery and used for mapping and ablation in the left ventricle. A transseptal approach was used for access to the left ventricle in 1 patient who had aortic stenosis. After catheters were in position, 5000 units of heparin were administered intravenously, followed by additional doses of 1000 units every hour. Pacing was performed with a programmable stimulator (Bloom Associates Ltd., Redding, PA, or Biotroniks, Erlangen, Germany).

If the ventricular tachycardia was not incessant, right ventricular programmed stimulation was performed using 4 extrastimuli [5]. Left ventricular mapping was performed, and at all sites with an abnormal ventricular electrogram (amplitude $\leq$0.5 mV and duration $\geq$60 msec), pacing trains of 8–15 stimuli were delivered at a cycle length 20–100 msec shorter than the VT cycle length. The pacing current was increased to a maximum of 10 mA and the pulse width to a maximum of 9 msec (2 msec in the last 12 patients) as needed to achieve capture. The onset of the pacing train was synchronized to the VT, with the initial coupling adjusted such that the first stimulus was delivered in late diastole. The coupling interval of subsequent drive trains was progressively shortened by 10–20 msec until there was concealed entrainment or capture without entrainment.

Electrodes 1 and 3 of the mapping catheter were used for bipolar pacing, and electrodes 2 and 4 were used for bipolar recording. The intracardiac electrograms and leads V1, I, II and III were displayed on an oscilloscope and recorded on paper at 100 mm/sec. The left ventricular electrograms were recorded simultaneously at gain settings of 20 and 80 mm/mV, with filter settings of 50 to 500 Hz. The recordings were stored on optical disk (Quinton, Bothell, WA, or Bard).

Radiofrequency Ablation

Radiofrequency energy was applied only at sites at which concealed entrainment was present. Concealed entrainment was defined as entrainment of VT without fusion of the QRS complexes on any of the 12 leads of the electrocardiogram, at multiple pacing cycle lengths [2,6]. Radiofrequency energy was delivered as a continuous, unmodulated sine wave at a frequency of 500 kHz (EP Technologies). Power was titrated automatically to maintain an electrode-tissue interface temperature of 60 °C. Applications of energy were delivered during VT and continued for at least 20 seconds, at which point energy delivery was discontinued if VT had not terminated. If the VT terminated during delivery of radiofrequency energy, the application was continued for 60 seconds. Programmed ventricular stimulation then was repeated to determine whether the ablated VT was still inducible. A successful outcome was defined as termination of the VT during an application of radiofrequency energy, and the inability to reinduce the VT using the complete programmed stimulation protocol.

Analysis of Data

Analysis of data was partially prospective (in the last 12 patients) and in part retrospective (in the first 17 patients) in nature. All of the pacing trains that were delivered at sites of concealed entrainment were analyzed. In addition, in the last 12 patients in this study, the pacing trains that were delivered at sites where there was not concealed entrainment also were analyzed.

If VT terminated during pacing, the electrograms were analyzed to determine whether termination occurred with (Figures 1 and 3) or without global ventricular capture (Figure 2). If the pacing train that terminated VT was associated with global ventricular capture, the QRS complexes during pacing were analyzed to determine whether they did or did not have the same configuration as during VT. When pacing did not alter the configuration of the QRS complexes compared to the VT, this was defined as orthodromic capture (Fig. 1). On the other hand, if the paced QRS complexes differed in configuration from the VT, this was defined as non-orthodromic capture (Fig. 3). In some cases, VT was terminated by pacing with and without global ventricular capture; in these cases, the mechanism was classified as termination without ventricular capture.

Continuous variables are expressed as mean $\pm$1 standard deviation. Comparisons were performed using Student's *t*-test, Chi-square analysis, or Fisher's exact test, as appropriate. P values less than 0.05 were considered to be significant.

Results

Results of Radiofrequency Ablation

Radiofrequency energy was delivered at 102 sites that displayed concealed entrainment during

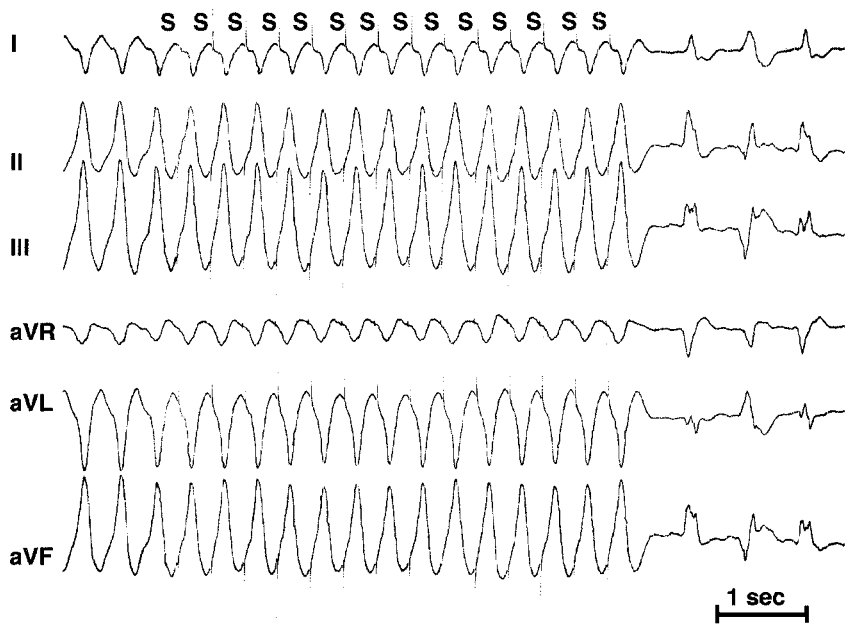

Fig. 1. *Shown are the frontal plane leads of a VT (CL 390 msec) which was terminated during pacing maneuvers with the mapping catheter. The catheter was located at the midseptal left ventricular wall. 14 pacing stimuli (S) were introduced during VT at a cycle length of 360 msec. There is capture with orthodromic conduction and this terminates the VT. Radiofrequency ablation at this site was successful.*

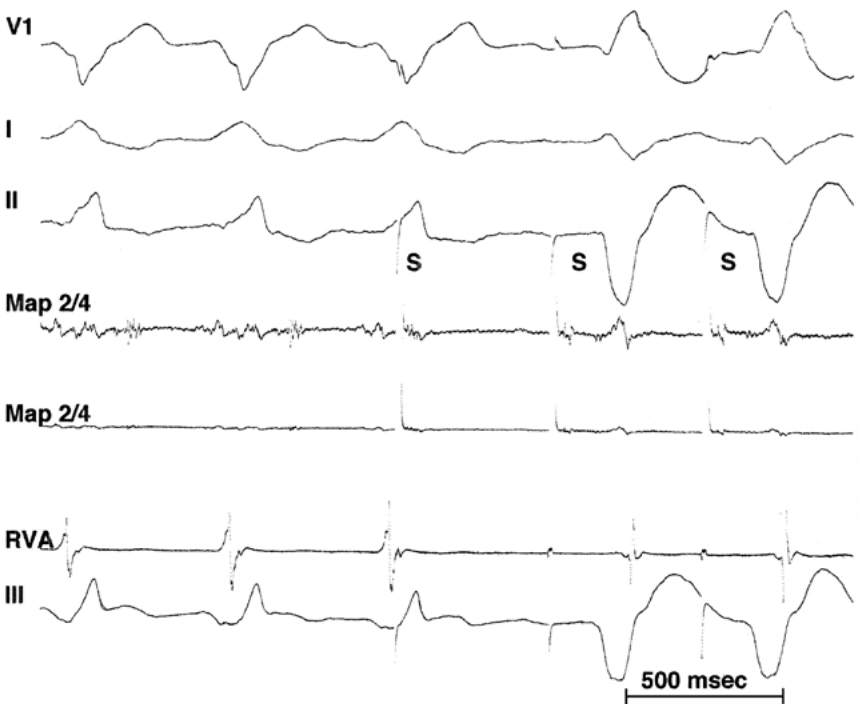

Fig. 2. *Shown are surface leads V1, I, II, III and intracardiac recordings from the mapping catheter (Map 2/4) and the right ventricular apex (RVA). Pacing was performed during VT and the VT terminated after the first non-capturing stimulus (S) of the pacing train. There is local but no global capture as shown by the tracings of the mapping catheter (Map 2/4). Note that the 3rd QRS complex is on time and that the preceeding p-wave does not capture the ventricle. Radiofrequency ablation at this site resulted in successful VT ablation.*

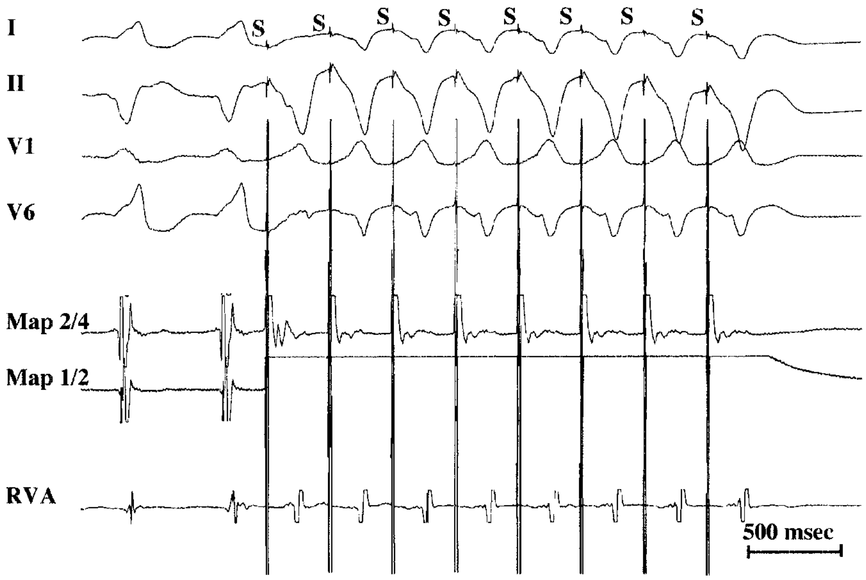

Fig. 3. *Shown are surface leads I, II, V1 and V6, the intracradiac recordings from the mapping catheter between electrodes 2 and 4 (Map 2/4), electrodes 1 and 2 (Map 1/2), and a recording from the right ventricular apex (RVA). Pacing was performed at the lateral left ventricular wall via the mapping catheter. There is non-orthodromic capture, with the QRS morphology during pacing being different than the VT morphology. Pacing resulted in termination of the ventricular tachycardia.*

52 VT's. In 3 of the 55 VT's, a site at which there was concealed entrainment could not be identified. Forty-one of the 55 VTs (75%) were successfully ablated.

Pacing at Sites of Concealed Entrainment (Tables 1 and 2)

A mean of 4.0 ± 3.5 pacing trains (range 1–16) were delivered at 102 left ventricular sites at which there was concealed entrainment, during 52 VT's. Pacing terminated the VT at 21 (21%) of the 102 sites at which there was concealed entrainment. Among the 52 VT's, termination by pacing occurred in 21 (40%).

Table 1. *Characteristics at sites of concealed entrainment at which pacing did and did not terminate ventricular tachycardia*

	VT termination	No VT termination	p-value
Sites (n)	21	81	
Successful sites	17/21	24/81	<0.001
S-QRS (msec)	176 ± 119	253 ± 158	0.06
EAT (msec)	140 ± 104	119 ± 77	0.3
S-QRS/VT CL	0.39 ± 0.27	0.55 ± 0.32	0.06

Abbreviations: S-QRS: stimulus-QRS interval; EAT: endocardial activation time; S-QRS/VT CL: stimulus-QRS/VT cycle length ratio.

Table 2. *Mapping variable categorized according to mechanism of VT termination by pacing*

Variables	No global ventricular capture	orthodromic capture	Non-orthodromic capture
n	10	4	7
S-QRS/VTCL	0.38 ± 0.31	0.23 ± 0.12	0.53 ± 0.25
S-QRS (msec)	148 ± 118	95 ± 40	251 ± 115
EGM-QRS (msec)	143 ± 113	95 ± 37	164 ± 119

Abbreviations as in Table 1. The following univariate comparisons were significant: S-QRS/VTCL orthodromic vs. non-orthodromic capture: p = 0.05; S-QRS orthodromic vs. non-orthodromic capture: p = 0.03.

VT termination at sites with concealed entrainment was a reproducible event and occurred 1.6 ± 1.0 times per termination site (range 1–5).

The pacing train terminated the VT at 17/41 successful ablation sites (41%), and at 4/61 unsuccessful ablation sites (7%, $p < 0.001$).

The specificity, sensitivity, and positive predictive value for successful ablation at sites with concealed entrainment where VT terminated during pacing were 94, 41, and 81%, respectively.

Termination without global ventricular capture was the most frequent mechanism (10/21, or 48%) by which pacing terminated VT at sites of concealed entrainment. Ablation of VT was successful at all of the pacing sites at which there was termination without global ventricular capture. The next most common mechanism of termination of VT by pacing was non-orthodromic capture (7/21, or 33%), and ablation was successful at 3 of these 7 sites. Termination with orthodromic capture occurred at 4 of the 21 sites (23%). Ablation of the VT was successful at each of these sites. Sites at which there was either termination without global capture or with orthodromic capture had a smaller mean stimulus-QRS/VT cycle length ratio as compared to sites at which there was termination with non-orthodromic capture (0.33 ± 0.26 vs. 0.55 ± 0.32; $p = 0.02$).

The mean cycle length of the pacing trains that did and did not terminate VT did not differ significantly (456 ± 65 vs. 439 ± 76 msec, $p = 0.4$). Likewise, the mean cycle length of the VT's that were and were not terminated by pacing did not differ significantly (451 ± 76 vs. 494 ± 94 msec $p = 0.2$). The mean initial coupling interval of trains that terminated the VT without global capture was significantly shorter than the mean initial coupling interval of the trains terminating VT with global capture (122 ± 23 msec vs. 338 ± 30 msec; $p < 0.001$).

The data obtained in the first 17 patients (retrospective part) were comparable with the data collected prospectively (prospective part) in the latter 12 patients as outlined in Table 4. The most frequent termination mode in the last 12 patients at sites with concealed entrainment was termination without global capture (5/5 terminations). All of these sites resulted in effective radiofrequency ablations.

Sites without Concealed Entrainment (Table 3)

A total of 725 pacing trains were delivered at 222 left ventricular sites that displayed an abnormal local electrogram, during 16 VT's. Twelve of the 16 VT's (75%) terminated at least once during left ventricular pacing. Ventricular tachycardia terminated at 38/222 pacing sites (17%). The mean cycle length of the pacing trains that did and did not terminate VT did not differ significantly (425 ± 84 vs. 367 ± 21 msec, $p = 0.3$). Termination of VT by pacing always occurred with non-orthodromic capture. The initial coupling interval of pacing trains terminating VT at sites without concealed entrainment was not significantly different from sites with concealed entrainment that terminated with global capture (334 ± 18 msec vs. 338 ± 30 msec, $p = 0.9$).

Table 3. *Mechanism of VT termination by pacing at sites with and without concealed entrainment*

	Concealed entrainment	No concealed entrainment	p-Value
Total number of sites	102	222	
Termination by pacing	21/102 (21%)	27/222 (12%)	0.5
Termination without global capture	10/21 (48%)	0/27 (0%)	<0.01
Non-orthodromic capture	7/21 (33%)	27/27 (100%)	<0.01
Orthodromic capture	4/21 (19%)	0/27 (0%)	0.01

Abbreviations: as above.

Table 4. *Comparison of characteristics of the first 17 patients compared to the following 12 patients*

Variables	First 17 patients	Latter 12 patients	p-Value
EF	0.29 ± 0.13	0.26 ± 0.08	0.5
VT CL	487 ± 88	469 ± 101	0.5
Sites analyzed	69/102	33/222	
VT term./per site	16/69	5/33	0.4

Abbreviations: EF: ejection fraction; VT CL: Ventricular tachycardia cycle length; VT term.: termination of VT.

Discussion

Main Findings

The results of this study demonstrate that VT often was terminated by pacing at sites where there was concealed entrainment in patients with a prior myocardial infarction. When this occurred, the most common mechanism of termination was by pacing without global ventricular capture, and another mechanism was pacing with orthodromic capture. Both of these mechanisms of pace-termination of VT were specific to sites at which there was concealed entrainment, and both were strongly predictive of successful catheter ablation by delivery of radiofrequency energy at the pacing site. These findings suggest that termination of VT either without global ventricular capture or with orthodromic capture is possible only at sites that are critical to the maintenance of reentry.

Sites with Concealed Entrainment

Termination of reentrant arrhythmias by subthreshold pacing stimuli has been described previously [7,8], and has been suggested to be helpful in identifying a critical component of reentry circuits [9]. Concealed entrainment also may be helpful in identifying a critical component of a VT reentry circuit, but concealed entrainment is not a specific finding and also may be observed at sites that are not critical for the maintenance of reentry

[1,6]. No prior studies have analyzed the utility of subthreshold stimuli at sites at which there is concealed entrainment. In the present study, termination without global ventricular capture was possible at a site of concealed entrainment in approximately 20% of VT's in which concealed entrainment could be demonstrated.

Single, subthreshold stimuli may prolong ventricular refractoriness when applied in close proximity to the site at which refractoriness is being measured [10,11]. If the subthreshold stimulus is delivered within a critical component of the reentry circuit, prolongation of refractoriness within that component potentially could result in termination of the ventricular tachycardia. Another possible mechanism resulting in termination of VT during subthreshold stimulation would be local capture of tissue which fails to propagate. However, this is difficult to demonstrate because the stimulus artifact obscures the recordings of electrodes 1/2 such that local electrograms immediately after the stimulus are not readily visible.

Termination of VT with orthodromic capture also was observed at sites of concealed entrainment. As reflected by the stimulus-QRS/VT CL ratio, this termination mode was observed at sites closer to the exit site. Haberl and Allessie [12] suggested that development of postrepolarization refractoriness may occur after premature stimuli; this might contribute to VT termination after cessation of pacing. Alternatively termination might be due to a rate dependant block in the zone of slow conduction with pacing. Stimulation close to the entry site of the segment of slow conduction results in orthodromic and antidromic wavefronts. If the stimulus occurs relatively early in diastole and the antidromic wavefront reaches the entry site before the orthodromic wavefront reaches the exit site, capture at the entrance can occur [13], resulting in a change in the QRS morphology. Again, timing is a critical factor, and concealed entrainment may be observed if the stimulus occurs later during diastole. Termination of the tachycardia occurs if the orthodromic wavefront from the stimulus encounters refractory tissue at the entrance site (termination with non-orthodromic capture). These sites were clearly separate from sites terminating with orthodromic capture, in that they were located further away from the exit site of the reentry circuit.

Sites without Concealed Entrainment

Although the incidence of termination of VT by pacing at sites without concealed entrainment was similar to the incidence at sites with concealed entrainment, the mechanism of termination differed substantially. Whereas pacing at sites of concealed entrainment usually terminated VT either with stimuli that did not result in global ventricular capture or with stimuli that resulted in orthodromic capture, at sites where there was not concealed entrainment, termination by pacing always occurred with non-orthodromic capture. This reflects the fact that none of the sites at which concealed entrainment did not occur were located within a critical portion of the reentry circuit. Therefore, pacing always resulted in local capture and a QRS configuration that differed from that of the VT.

Limitations

This study has several limitations. Firstly, the results of this study apply only to VT's that are hemodynamically-tolerated in patients with prior myocardial infarction. Secondly, many of the patients were being treated with amiodarone, and this may have influenced the ability of pacing trains to terminate VT. Thirdly, the study was in part retrospective in nature and the prevalence of termination with or without global capture may have been underestimated. However in the last 12 patients data were assessed in a prospective manner and there was no difference with respect to patient characteristics as well as the prevalence of the VT termination and the results of radiofrequency ablations at sites with concealed entrainment displaying termination of VT during pacing.

Conclusion

Termination by pacing may be observed in approximately 40% of VT's at sites of concealed entrainment in patients with prior myocardial infarction. Termination of VT by pacing at sites of concealed entrainment either without global ventricular capture or with orthodromic capture is highly specific for the identification of a critical component of the reentry circuit.

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