Mapping and Ablation of Ventricular Tachycardia Guided by Virtual Electrograms Using a Noncontact, Computerized Mapping System

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OBJECTIVES
The purpose of this study was to describe a computerized mapping system that utilizes a noncontact, 64 electrode balloon catheter to compute virtual electrograms simultaneously at 3,360 left ventricular (LV) sites and to assess the clinical utility of this system for mapping and ablating ventricular tachycardia (VT).

BACKGROUND
Mapping VT in the electrophysiology laboratory conventionally is achieved by sequentially positioning an electrode catheter at multiple endocardial sites.

METHODS
Fifteen patients with VT underwent 18 electrophysiology procedures using the noncontact, computerized mapping system. A 9F 64 electrode balloon catheter and a conventional 7F electrode catheter for mapping and ablation were positioned in the LV using a retrograde aortic approach. Using a boundary element inverse solution, 3,360 virtual endocardial electrograms were computed and used to derive isopotential maps. An incorporated locator system was used in conjunction with or instead of fluoroscopy to position the conventional electrode catheter.

RESULTS
A total of 21 VTs, 12 of which were hemodynamically-tolerated and 9 of which were not, were mapped. Isolated diastolic potentials, presystolic areas, zones of slow conduction and exit sites during VT were identified using virtual electrograms and isopotential maps. Among 19 targeted VTs, radiofrequency ablation guided by the computerized mapping system and the locator signal was successful in 15.

CONCLUSIONS
The computerized mapping system described in this study computes accurate isopotential maps that are a useful guide for ablation of hemodynamically stable or unstable VT. (J Am Coll Cardiol 2000;35:414–21) © 2000 by the American College of Cardiology

Mapping ventricular tachycardia (VT) in the electrophysiology laboratory conventionally is performed by sequentially positioning an electrode catheter at multiple endocardial sites. The purpose of this study was to describe a computerized mapping system that utilized a noncontact, 64 electrode balloon catheter to compute virtual electrograms simultaneously at 3,360 left ventricular (LV) sites using a boundary element inverse solution. The virtual electrograms were validated by comparison with conventionally-recorded electrograms, and the utility of the system as a guide for radiofrequency ablation of VT was assessed.

METHODS
Patients. The subjects of this study were 15 consecutive patients who underwent an electrophysiology procedure with a view towards radiofrequency ablation of VT who provided written informed consent under a protocol approved by the Human Research Committee at the University of Michigan. The patients consisted of 13 men and 2 women with a mean age of 70 ± 6 years (Table 1). Thirteen of the patients had a history of myocardial infarction (MI), and 2 patients had a nonischemic dilated cardiomyopathy. The mean LV ejection fraction was 0.30 ± 0.15. Each of the 15 patients had previously undergone defibrillator implantation for the treatment of life-threatening ventricular arrhythmias. The indications for ablation of VT were frequent episodes of VT that occurred immediately before defibrillator implantation in 3 patients, sustained VT below the rate cutoff of the defibrillator in 1 patient and frequent...
defibrillator therapies in 11 patients. All implanted defibrillators provided stored electrograms. Two of the 15 patients had previously undergone an unsuccessful radiofrequency catheter ablation procedure using conventional techniques. Before the mapping and ablation procedure, a mean of 1.3 ± 0.7 antiarrhythmic agents had been unsuccessful, including amiodarone in 9 of the 15 patients. At the time of the ablation procedure, 9 patients were being treated with amiodarone, 5 with mexiletine, 2 with sotalol, 2 with procaainamide, 1 with quinidine and 1 with lidocaine.

Conventional electrophysiologic testing protocol. Electrophysiology procedures were performed in the postabsorptive state. A 7F quadrapolar electrode catheter was inserted into a femoral vein and positioned at the apex of the right ventricle. The inducibility of VT was assessed by programmed ventricular stimulation with four extrastimuli at the right ventricular apex using basic drive cycle lengths of 350, 400 and 600 ms (1).

Conventional mapping and ablation were performed with a 7F quadrapolar electrode catheter that had 2-5-2 mm interelectrode spacing (EP Technology Inc., Sunnyvale, California) inserted percutaneously into a femoral artery and positioned in the LV. This catheter had a deflectable shaft, a 4 mm distal electrode and a thermistor imbedded in the tip of the distal electrode.

Overview of the on-line, noncontact mapping system. The mapping system (Endocardial Solutions, Inc., St. Paul, Minnesota) was a computerized (Silicon Graphics, Mountain View, California) electrophysiology recording system that, in conjunction with a 64 electrode, noncontact balloon catheter, constructed a three-dimensional model of the endocardium of the LV, provided a locator system to identify the position of a conventional electrode catheter within the model and computed 3,360 virtual endocardial electrograms (2). The virtual electrograms could be computed in either a unipolar or bipolar format. In this study, unipolar electrograms were utilized for virtual electrograms and isopotential maps. Multiple electrograms from any portion of the three-dimensional LV endocardial reconstruction could be viewed by interactively selecting any of the 3,360 virtual electrograms in a linear or a grid format with the mouse pointer (Fig. 1). The system displayed a color, dynamic three-dimensional isopotential map derived from the virtual electrograms, based upon the amplitude of the electrograms (Fig. 1). The dynamic isopotential map

Table 1. Clinical Characteristics

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* = mapped during second procedure.

Abbreviations and Acronyms

LV = left ventricle or ventricular
MI = myocardial infarction
VT = ventricular tachycardia

Ant = anterior; Anterosep = anteroseptal; CAD = coronary artery disease; CVA = cerebrovascular accident; EF = ejection fraction; Inf = inferior; MI = myocardial infarction; MI = ventricular tachycardia not inducible after 64-electrode balloon; NA = not applicable; NICM = nonischemic cardiomyopathy; Post = posterior; Postlat = posterolateral; Pt = patient; VT Hemo Stable = hemodynamically stable ventricular tachycardia.

* = mapped during second procedure.
depicted the electrical potential from each virtual electrogram throughout the cardiac cycle, at intervals of 0.83 ms. The leading edge of the depolarization wavefront is a negative potential (3). By adjusting the color gain such that the negative potential of the leading edge of depolarization was always white, the advancing edge of a wave of depolarization could be observed (Fig. 2).

The surface ECG leads and intracardiac electrograms from the conventional electrode catheters were recorded by the computerized recording system. The filter settings for the intracardiac electrograms were 0.1 to 300 Hz. The electrograms recorded with the conventional LV catheter were used for comparison with the calculated virtual electrograms.

**Noncontact 64 electrode balloon catheter.** The 64 electrode noncontact electrode balloon catheter (Endocardial Solutions, Inc.) was 9F in diameter. The catheter was made of polyurethane and had two lumens. A central lumen compatible with a 0.035 in. guidewire was open at the distal end of the catheter, which had a pigtail shaped tip. Fifteen millimeters from the end of the catheter there was an

**Figure 1.** Display of virtual electrograms. Multiple virtual electrograms were simultaneously viewed in a linear or grid format after being selected at the area of interest with the computer mouse. An isopotential map during ventricular tachycardia (VT) (cycle length 380 ms) is shown in these three panels. In each panel, the left ventricular reconstruction is shown with the septum, base and apex indicated. The chamber is shown in an open view of the entire endocardial reconstruction. The anterior septum on the far left of each endocardial reconstruction is anatomically continuous with the anterior septum on the far right of each model. In each panel, the isopotential map identifies the site of endocardial activation associated with the onset of the QRS complex during VT. The maximum negative potential, representing the leading edge of the wave of depolarization, is shown in white. A wireframe depiction of the inflated noncontact balloon catheter is shown in the top panel but not in the lower panels. In the top panel, eight closely-spaced virtual electrograms have been selected for viewing in a linear format. In the middle panel, a linear format of eight virtual electrograms with a larger interelectrode distance is displayed. An example of 16 virtual electrograms in a grid format is provided in the bottom panel. The letters on the isopotential map correspond to the virtual electrograms. Surface ECG lead I also is shown.
ellipsoidal, polyurethane balloon with an expanded volume of 7.5 ml. The second lumen terminated in the balloon. A stainless steel, polyamide-coated, braided mesh wire with 64 electrodes was present on the surface of the balloon. When the balloon was expanded, each electrode was separated by 4 to 7 mm.

To position the electrode balloon catheter in the heart, a 0.035 in. guidewire was placed in the central lumen of the electrode balloon catheter. Intravenous heparin was administered to achieve an activated clotting time greater than 350 s. The electrode balloon catheter remained in place for 5 h.

Locator signal and the 3-dimensional left ventricular model. A signal used to locate the tip electrode of the conventional mapping catheter was generated by passing a 5.68 kHz signal through the electrode (Fig. 3). The strength of the signal recorded at each of the 64 electrodes was used to compute the location of the tip electrode in relation to the electrode balloon catheter using a point source–point sink model.

A three-dimensional model of the endocardium of the LV was computed using a convex hull algorithm applied to the collection of locator points gated to end diastole. This model was used in combination with the electrograms recorded from the 64 electrodes on the balloon catheter to compute the 3,360 virtual electrograms.

Validation of virtual electrograms. The conventional mapping catheter was positioned randomly at three different endocardial sites in the LV. At each location, unipolar recordings from the computerized system and from the conventional catheter were obtained during sinus rhythm, right ventricular pacing and VT. The actual and virtual recordings were compared by correlation coefficient for morphology and by comparing the onset of the electrograms using filter settings of 0.1 Hz to 300 Hz. Electrogram morphologies were considered to be equivalent if the correlation coefficient was 0.8 to 1.0. The time of onset of a virtual electrogram was compared with that of the actual electrogram recorded with the conventional catheter. This was accomplished by determining when the maximum correlation coefficient for morphology was achieved relative to the onset of the calculated virtual electrogram. Electrogram onset was defined as the first major deflection to cross the isoelectric baseline.

Mapping of ventricular tachycardia. The spontaneously occurring VT was documented with a 12 lead ECG in eight patients, and the cycle length of the clinical VT was determined from monitor strips or from intracardiac electrograms stored in the defibrillator in seven patients. If a 12 lead ECG was not available, a VT induced by programmed stimulation that had a cycle length within 10 msec of the spontaneous VT was presumed to be the clinical VT. Additionally, because VTs of different morphologies may share critical portions of their circuits (4), other VTs, whether hemodynamically stable or unstable, were targeted for ablation if the clinical VT was not inducible by programmed ventricular stimulation or if a particular VT was easily inducible by programmed stimulation.
Ventricular tachycardia was induced with programmed stimulation and then recorded in less than 10 s using the noncontact computerized mapping system. The computational time required to construct the map was less than 30 s. The time required for investigator analysis of the isopotential maps is not available and typically ranged from 15 min to 2 h. Mapping of VT was accomplished using the virtual electrograms and isopotential maps in 13 patients. Because of a complication, VT was not mapped in two patients.

Mapping was performed by first aligning the map time-course with the time of QRS onset and then finely adjusting the color controls to reveal the exit site (Fig. 2). In any given isopotential map, the map colors corresponded to a specific electrogram amplitude. However, the color gain was adjusted to maximize the color differences as the electrogram amplitude changed throughout the cardiac cycle. With the isopotential map and by selection of virtual electrograms at various locations in the LV reconstruction, presystolic activation was traced as far back as possible (Fig. 2). The virtual electrograms and isopotential maps also were used to identify isolated diastolic potentials, sites of presystolic endocardial activation during VT, zones of slow conduction and VT exit sites. Each of these was used to identify potential target sites for ablation. Target sites for ablation were identified with the computerized mapping system. Subsequently, the conventional ablation catheter was directed to the target site using fluoroscopy and the locator signal emanating from the tip electrode.

Catheter ablation. Radiofrequency energy was delivered by a generator that supplied a continuous unmodulated frequency of 500 kHz (EP Technology, Inc., Sunnyvale, California). Whenever possible, radiofrequency energy was delivered during VT. Power was titrated to a target temperature of 60°C. All applications were continued for at least 10 s after the target temperature was obtained. If the VT terminated, the application was continued for 60 s. If the radiofrequency energy was delivered during sinus rhythm, then the application of energy was continued for 60 s. After each application of radiofrequency energy, the inducibility of VT was assessed by programmed ventricular stimulation (1).

For a hemodynamically-tolerated VT, successful ablation was defined as termination of the VT during an application of radiofrequency energy and the inability to reinduce the VT with programmed ventricular stimulation. For VT associated with profound hypotension, radiofrequency energy was delivered during sinus rhythm and efficacy was assessed by programmed ventricular stimulation using four premature extrastimuli (1). Nontargeted VTs remained inducible with programmed ventricular stimulation after applications of radiofrequency energy. Ablation procedure duration was defined as the time after investigator analysis of the computerized noncontact mapping data and the completion of the ablation procedure.
Follow-up. The study protocol was designed to include clinical evaluation at one month of follow-up. All surviving patients were evaluated one month after the procedure by one of the investigators.

Analysis of data. Continuous variables are expressed as mean ± SD and were compared with a paired or unpaired t test, as appropriate. The means of the signal analysis data were determined for each patient. These mean values were used to determine the means and standard deviations for the entire study population. Nominal variables were compared by chi-square analysis. A probability value < 0.05 was considered statistically significant.

RESULTS

Comparison of virtual and actual electrograms. Virtual and actual electrograms from a total of 398 sites during sinus rhythm, right ventricular pacing and VT were compared (Fig. 4). The mean correlation coefficient for morphology between all of the actual and virtual electrograms was 0.81. For the 231 electrograms recorded at endocardial sites within 3.4 cm of the equatorial center of the balloon catheter, the correlation coefficient for morphology was 0.86, compared with 0.75 for the 169 electrograms recorded at endocardial sites beyond this distance (p < 0.0001).

The mean and median difference in onset between the actual and virtual electrograms was 3.0 ± 2.8 ms, and 1.49 ms, respectively.

Mapping of ventricular tachycardia. Mapping and ablation of 19 VTs was attempted in 14 patients (Table 1). The mean cycle length of these VTs was 383 ± 111 ms (range 230 to 670 msec; Table 1). Ten of the VTs were hemodynamically-tolerated (mean cycle length 441 ± 127 ms) and 9 were not (mean cycle length 314 ± 66 ms).

The exit site and sites of presystolic activation were identified for each mapped VT (Fig. 2). The computerized mapping system identified an isolated diastolic potential in each of the two VTs in which one was recorded with a conventional catheter (Fig. 3A). During concealed entrainment with different stimulus-QRS intervals, the computerized mapping system identified the same exit site as during VT and an activation pattern consistent with stimulation within a zone of slow conduction at variable distances from the exit site (Fig. 3B). The entire reentrant circuit was identified in only one ventricular tachycardia (Fig. 3).

Ablation results. Among 19 VTs that were targeted for ablation, 15 (78%) were successfully ablated (Table 1). The mean number of radiofrequency energy applications was 5.8 ± 5.1. Successful ablation was achieved for five of nine VTs that were not hemodynamically-tolerated. These VTs would not have been amenable to mapping using conventional techniques other than pace mapping.

The reasons for unsuccessful ablation of four VTs were the inability to maneuver the ablation catheter to the target site, proximity of the target site to the bundle of His or a complication that forced the ablation procedure to be aborted.

The mean time required to perform the ablation procedure was 125 ± 68 min, and the mean fluoroscopic time was 79 ± 23 min.

Complications. There were three complications during the 18 procedures (Table 1). The conventional mapping catheter caused LV perforation and cardiac tamponade in one patient who was successfully managed by pericardiocentesis. A second patient developed global ischemia and transient electromechanical dissociation after the third induction of a VT associated with hypotension. This VT was inadvertently induced three times, and was not the VT targeted for ablation. The patient died several days later due to progressive hemodynamic deterioration. A third patient noted clumsiness in his left hand 12 h after the procedure. Computer tomography scans were consistent with a small parietal cerebrovascular accident. After one month, he had only a minor motor deficit.

Follow-up. During the preablation period of 1.4 ± 0.9 months (range 0.2 to 3 months), the 12 patients with a previously implanted defibrillator received a mean of 19 ± 32 defibrillator therapies per month (range 1 to 111 therapies per month). At one month of follow-up, the surviving 11 patients with a defibrillator implanted before the ablation procedure received 0.6 ± 1.4 therapies per month (p = 0.04 compared with before ablation).

Among the overall cohort of 14 patients who survived after the ablation procedure, 10 patients received no def-
brillator therapies after ablation, and four patients received a mean of 2.0 ± 1.7 defibrillator therapies per month.

DISCUSSION

Major findings. The results of this study demonstrate that the noncontact, cardiac mapping system described in this study is able to accurately compute virtual ventricular electrograms. Mapping was facilitated by the ability to view virtual electrograms from any portion of the three-dimensional LV endocardial model without moving a conventional catheter to each area of interest. The system accurately identified the presence of diastolic potentials, areas of presystolic activation, zones of slow conduction and VT exit sites. Hemodynamically stable and unstable VT were successfully ablated using the noncontact mapping system and locator signal.

Validation of isopotentials. During reentrant VTs, dynamic isopotential maps successfully identified various components of the reentry circuit, including the exit site and sites of diastolic activity. Furthermore, the dynamic isopotential maps during concealed entrainment with variable stimulus-QRS intervals demonstrated a pattern of activation consistent with stimulation within a zone of slow conduction at variable distances from the exit site. Additional support for the accuracy of the isopotential maps was provided by the successful outcome of catheter ablation when using the isopotential maps to identify target sites.

Prior studies. Noncontact isopotential mapping was first demonstrated by Taccardi, et al. (5) in a dog model in 1987. The system utilized by these investigators predicted the site of origin of VT within 20 mm and calculated electrograms within 10 ms of the actual electrograms (6,7). The validity of a boundary element inverse solution to support a noninvasive cardiac mapping system was demonstrated (8). A few reports have validated the mapping system described herein (2,9–11). An experimental study (2) has demonstrated the accuracy of the locator signal to within 4 mm (2). The system utilized by these investigators predicted the site of VT within 2.0 ± 1.7 mm of the actual electrograms. Mapping was facilitated by the ability to view virtual electrograms from any portion of the three-dimensional LV endocardial model without moving a conventional catheter to each area of interest. The system accurately identified the presence of diastolic potentials, areas of presystolic activation, zones of slow conduction and VT exit sites.

Comparison with other mapping techniques. Mapping and ablation of VT has been accomplished with activation or isochrone maps, isopotential maps and with the use of a variety of catheter-based endocardial techniques (3,4,12–24). Conventional catheter-based techniques to map VT have included concealed entrainment, identification of an isolated diastolic potential, identification of the earliest presystolic endocardial activation during VT and pace mapping during sinus rhythm (12–16). Each of these techniques, except pace mapping, requires that VT is present during mapping. Therefore, if the VT is not tolerated hemodynamically, conventional mapping is limited to pace mapping during sinus rhythm.

Recently, a computerized mapping system, which reconstructs the three-dimensional chamber geometry and overlays endocardial activation data, has been described (25–28). However, this system requires serial mapping of endocardial sites with a contact catheter (25–28). Therefore, as opposed to the system described herein, the previously described system is not useful for mapping VT associated with hemodynamic instability.

Limitations of the noncontact computerized mapping system. The system utilized in this study calculates virtual electrograms only at the endocardial surface. Because some VTs utilize the epicardium for at least part of the reentry circuit (29–33), this may represent a limitation of the mapping system. In fact, in this study, the entire diastolic component of the VT reentry circuit was identified for only one VT. A second potential limitation of the mapping system is that the endocardial geometry model is acquired during the baseline rhythm, and the virtual electrograms calculated during other arrhythmias are fit to this model. This limitation may be more important in a vigorously contracting chamber than in a poorly functioning ventricle.

Clinical implications. Heretofore, mapping of VT in the electrophysiology laboratory has been limited to patients who have VT that is hemodynamically tolerated, and many patients with VT do not meet this criterion. The mapping system described in this study and previously (11) may greatly expand the indications for radiofrequency ablation of VT by allowing mapping in the electrophysiology laboratory of VT that are not hemodynamically tolerated. While the results of this initial study are promising, additional clinical evaluation of the risks and benefits associated with this mapping system are required.

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REFERENCES


