New Method for Nonfluoroscopic Endocardial Mapping in Humans
Accuracy Assessment and First Clinical Results

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Background—Accurate mapping of the site of origin and activation sequence of a cardiac arrhythmia is essential for a successful catheter ablation procedure. To achieve this, precise and reproducible catheter manipulation is mandatory. The aim of this study was (1) to assess the accuracy of a new nonfluoroscopic mapping system in humans and (2) to report the first result of endocardial activation mapping with this system during sinus rhythm and several types of supraventricular and ventricular tachycardias.

Methods and Results—Fifteen patients were studied. Accuracy measurements were performed in 5 of them (patients 5, 6, 7, 8, and 14). The distances between two subsequent catheter positions in the inferior caval vein as determined by the nonfluoroscopic mapping system were compared with measurements made with calipers by four independent investigators using identification marks on the catheter shaft. The difference between these two methods was 0.95±0.8 mm. In 15 patients, activation of the right atrium and/or the right or left ventricle was recorded during sinus rhythm. Three-dimensional activation maps were constructed in patients with atrial and ventricular tachycardias and Wolff-Parkinson-White syndrome.

Conclusions—With this new nonfluoroscopic mapping technique, accurate positioning of the catheter tip is possible. A three-dimensional activation map can be reconstructed during sinus rhythm and during supraventricular and ventricular tachycardias of different compartments of the heart. (Circulation. 1998;97:2426-2432.)

Key Words: mapping n arrhythmia n ablation

Accurate mapping of the site of origin or activation sequence of a cardiac arrhythmia is essential for a successful radiofrequency (RF) catheter ablation procedure. With the use of different kinds of plaque and sock arrays, high-resolution epicardial and endocardial activation maps of arrhythmias have been made during open heart surgery in patients with Wolff-Parkinson-White syndrome,1 ventricular tachycardias after myocardial infarction,2-3 atrial tachycardia,4,5 and atrial fibrillation.6 In the intact heart, endocardial catheter mapping of an arrhythmia is difficult because only a limited number of intracardiac electrodes can be introduced, allowing simultaneous activation mapping from only a few sites.7 During endocardial catheter mapping, the relation between the intracardiac recording and the anatomy of the heart is made by the investigator using bidirectional fluoroscopy. Positioning of the catheter with the use of fluoroscopy can be time consuming and is often poorly reproducible. For this reason, several types of multipolar catheters (eg, basket) are now being developed to make mapping more accurate and faster.8

We describe a new nonfluoroscopic endocardial mapping technique using catheters instrumented with a sensor in the distal tip to allow their location in space using an electromagnetic field of low intensity applied outside the body. The catheter position and orientation in space are processed together with the intracardiac recordings. A three-dimensional (3D) electroanatomic activation map is constructed in real time and displayed on a graphic computer.

The purpose of this study was (1) to measure the accuracy of the location of this catheter within the human body and (2) to report our experience from the first 15 patients in whom this mapping method was used.

Methods

This study was performed in 15 patients (Table 1) who were admitted for electrophysiological evaluation and subsequent catheter ablation of their arrhythmia. All antiarrhythmic medication was stopped at least five half-lives before the investigation. No patient was taking amiodarone.
Nonfluoroscopic Mapping System

The system has recently been described in detail. In short, the nonfluoroscopic mapping system (CARTO) consists of a location pad positioned under the bed of the patient, two catheters instrumented with a sensor and reference (REF) catheter, a mapping system, and a graphic computer (Silicon Graphics).

The location pad generates a magnetic field of very low intensity (0.02 to 0.5 G). In the distal part of the steerable mapping (STAR) catheter, a sensor is mounted. This sensor gives information about the position (x, y, and z axes) and the rotation (pitch, yaw, and roll) of the distal catheter segment. The accuracy of the sensor position in this low magnetic field is 0.8 mm and 5°.

From the distal tip of the catheter, a unipolar or bipolar signal can be recorded whose timing is related to a reference signal. In this way, activation times are obtained in relation to the position of the catheter in the heart.

Sequential recording of several points by dragging the catheter along the endocardium allows a real-time construction of a 3D activation map. An icon of the catheter is displayed together with this 3D map on the computer screen, which enables catheter manipulation in relation to the 3D map.

A minimum of six points, three at the top and three at the lower border of the compartment that is mapped, are needed to make a first 3D image.

In addition to the mapping catheter, a second catheter is instrumented with a sensor. The spatial information from this catheter is used to detect small changes in intracardiac position due to respiration or movement of the patient. In the computer, these small changes of the REF catheter are used to correct the spatial information of the mapping catheter.

Measurement Procedure

The mapping and reference catheters are positioned in the heart under fluoroscopic guidance. The reference electrode is preferentially positioned contralateral to the compartment that is being mapped. This reduces the risk of dislodging the position of the reference catheter because of manipulation of the mapping catheter. After six points are acquired with the mapping catheter by use of fluoroscopy, a 3D map is generated. Further catheter handling can now be guided by the 3D image in which the icon is displayed. Fluoroscopy is only needed if the mapping catheter slips outside the compartment that is being mapped.

Measurements are incorporated in the 3D map when two criteria are met: the stability criterion in space and the stability criterion in local activation time (LAT). To check stability, two consecutive measurements are compared. For the stability criterion, we used 4 mm; for the LAT, 4 ms was used as a default.

The operator analyzed signals, and if the signals were accepted as valid, they were brought into the 3D map. The 3D activation map was updated with every accepted point.

Accuracy Assessment

In five patients, two 9F sheaths (60 cm long) were advanced under fluoroscopic guidance from the left and right femoral veins into the inferior caval vein just below the right atrium. The sheaths were positioned outside the heart to avoid movement by contraction of the heart. The reference catheter was positioned in the distal part of one sheath so that the tip of the catheter was within the sheath. The mapping catheter was positioned in the other sheath at the same level. This catheter was withdrawn in the direction of the femoral vein in 14 to 19 steps.

Every step was measured by the CARTO system and by making an incision with a surgical blade on the catheter shaft at the entrance of the sheath. After the catheter had been removed from the sheet, the distances between the markings on the catheter were measured with calipers by four investigators and averaged. The difference between the distances, as measured by the investigators and as measured with the CARTO system, was calculated.

Results

Accuracy Assessment

As discussed in the “Methods” section, the mapping electrode in five patients was withdrawn 14 to 19 times (average, 16±1.9) per experiment over a distance of 141.4±30.6 mm (range, 101.8 to 184.9 mm). Per step, the distance was 5.5 to...
TABLE 2. Number of Points for Three-dimensional Map (Before and After Editing) and Time Needed to Construct Map

<table>
<thead>
<tr>
<th>Patient</th>
<th>Number of Points Before Editing</th>
<th>Number of Points After Editing</th>
<th>Time, min</th>
<th>Compartment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65</td>
<td>62</td>
<td>53</td>
<td>LV</td>
</tr>
<tr>
<td>2</td>
<td>52</td>
<td>49</td>
<td>43</td>
<td>RA</td>
</tr>
<tr>
<td>3</td>
<td>107</td>
<td>102</td>
<td>30</td>
<td>RA</td>
</tr>
<tr>
<td>4</td>
<td>142</td>
<td>134</td>
<td>43</td>
<td>RA</td>
</tr>
<tr>
<td>5</td>
<td>76</td>
<td>73</td>
<td>37</td>
<td>RA</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
<td>56</td>
<td>30</td>
<td>RV</td>
</tr>
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<td>RA</td>
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<td>RA</td>
</tr>
<tr>
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<td>66</td>
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<td>19</td>
<td>LA</td>
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<tr>
<td>15</td>
<td>58</td>
<td>56</td>
<td>39</td>
<td>LV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean ± SD</th>
<th>88.9 ± 29.7</th>
<th>74.7 ± 26.6</th>
<th>35.7 ± 17.8</th>
</tr>
</thead>
</table>

Range 50–170 38–134 14–97

LV indicates left ventricle; RA, right atrium; RV, right ventricle; and LA, left atrium.

14.9 mm (average, 8.73±1.61 mm; median, 8.8 mm) and 6.1 to 17.7 mm (average, 9.7±1.8 mm; median, 10.2 mm), as measured with the CARTO system and calipers, respectively, by four independent investigators. The difference between the distance as measured with the CARTO system and the averaged catheter incision values was 0.95±0.8 mm (median, 0.86 mm).

**Endocardial Activation Studies**

In Table 2, information is given about the number of points that were serially collected to construct a 3D map. In 27 maps, 50 to 170 points were recorded (mean, 88.9±29.7). It took 35.7±17.8 minutes to collect those points. In patient 12, it took 97 minutes to record 170 points. It took so long in this patient because the ventricular tachycardia stopped frequently owing to catheter manipulation and had to be reinitiated. The definite map, after editing, was composed of 74.7±26.6 points. The main reason points were skipped was a marginal stability in space, LAT, or both. The majority of points were collected manually (not in the semiautomatic mode).

**Right Atrial Activation**

During construction of maps of the atrium, the REF catheter was positioned in the coronary sinus.

**Sinus Rhythm**

Figure 1 shows the activation sequence of the right atrium during sinus rhythm. The activation sequence is color coded, starting with red and going to purple. The anatomic orienta-
tion points are the superior caval vein, coronary sinus, inferior caval vein, and tricuspid valve. In the right atrium, the earliest endocardially activated area is the transition of superior caval vein to the right atrium. This represents the activation of atrial muscle at the exit site of the sinus node (Figure 1, Top). Activation then proceeds in a posterior direction where anatomically the crista terminalis is situated, and spreads over the entire atrium (Figure 1, Bottom). In the 10 patients in whom right atrial endocardial activation maps were recorded, the total right atrial activation time from the sinus node exit to the AV ring and coronary sinus os ranged from 64 to 110 ms (mean, 83.7 ± 14.7 ms).

Atrial Tachycardia
Figure 2 (top) shows an activation map of the right atrium during atrial tachycardia. In contrast to the activation sequence during sinus rhythm, the earliest activated site (red area) is in the anterolateral part of the right atrium 1.5 cm above the tricuspid valve. Activation then spreads radially in a superior and posterior direction opposite to the normal activation sequence during sinus rhythm. During this atrial arrhythmia, endocardial activation of the right atrium was completed in 92 ms. Endocardial activation during sinus rhythm, after successful RF ablation of the atrial tachycardia, is shown in Figure 2, bottom.

Activation of the Left Atrium
During sinus rhythm, a mapping catheter was advanced transseptally into the left atrium (Figure 3). Earliest activation of the left atrium was recorded anterior from the septum, where anatomically the bundle of Bachmann is located (the red area). Activation then proceeds radially in the direction of the mitral valve. The last part to be activated is the lateral wall of the left atrium.

Activation of the Right Ventricle
The activation sequence of the right ventricle during sinus rhythm is shown in Figure 4. Note that in contrast to the map of the right atrium during sinus rhythm, several areas are activated early, as indicated by the red and yellow areas. One red area is located ≈ 1 cm distal to the site where the His bundle potential could be recorded. A second early-activation area is in the low inferoseptal area. This could represent the area where the right bundle activates the right ventricular endocardium. The part of the right ventricle last activated is the inferior and posterobasal area. In the seven patients in whom this was recorded, total activation of the endocardium of the right ventricle during sinus rhythm was completed within 37 to 52 ms (mean, 45.1 ± 10.1 ms).

Activation of the Left Ventricle
During mapping of the left ventricle, the reference catheter was positioned in the right ventricular apex. This was done to ensure correct and simultaneous movement with the roving ventricular electrode even if AV dissociation was present during ventricular tachycardia.

Patient 1 suffered from an anteroseptal myocardial infarction 4 years before the present study. Ventricular tachycardias that were hemodynamically well tolerated were recorded for the first time 2 years after myocardial infarction. Recurrent episodes of ventricular tachycardia occurred in spite of antiarrhythmic drug treatment.

The 12-lead ECGs obtained during sinus rhythm and ventricular tachycardia are shown in Figure 5. Analysis of the wide QRS tachycardia suggests a location of the tachycardia in the inferoseptal region. The endocardial activation sequence of the left ventricle during ventricular tachycardia is illustrated in Figure 6. The
map consists of 72 sequential points. Earliest endocardial activity was located in the infero-apico-septal region at the base of the papillary muscle. Endocardial activation then proceeded toward the lateral wall. Total activation time of the endocardium of the left ventricle during ventricular tachycardia was 69 ms. Parts of the ventricle (especially anterior and basal) were not mapped. The explanation for this incomplete map was twofold: (1) this was the first patient in whom we made an electroanatomic activation map, and (2) the first-generation catheter was relatively stiff at the tip, limiting maneuverability in some parts of the ventricle.

During sinus rhythm (Figure 7), the earliest activation was found in high anterolateral and mid-inferoseptal locations. The two early-activated areas were sites where anatomically
the anterior and posterior fascicles are situated. The apical part of the left ventricle could not be mapped in detail during sinus rhythm.

Complications
The STAR (type F-curve, first version) catheter has a rigid segment due to implementation of the sensor into the distal part of the catheter. This limits steerability and maneuverability. When we tried to map the ventricle, problems occurred in two patients. In patient 8, the ascending aorta was narrow compared with the long, stiff, distal segment of the catheter, preventing retrograde passage of the aortic valve, and the procedure was stopped.

In another patient (patient 5), right atrial and ventricular activations were mapped. The patient was heparinized. Subsequently, a standard RF catheter ablation of the slow AV nodal pathway was performed for AV nodal reentrant tachycardias. At the end of the procedure, the patient complained of chest pain on movement and inspiration, suggesting a pericardial origin. In the next 48 hours, progressive pericardial effusion developed that required drainage. Sanguinolent fluid (150 mL) was removed, suggesting a perforation. The perforation site (in the right atrium or right ventricle) was not identified. The patient recovered uneventfully.

Discussion
Since the introduction of RF catheter ablation as a therapeutic modality, many arrhythmias can be cured. In particular, arrhythmias associated with Wolff-Parkinson-White syndrome, AV nodal reentrant tachycardia, and ventricular tachycardias in a structurally normal heart have been successfully treated with this technique. Less satisfactory results are obtained in arrhythmias arising in hearts with altered anatomy, as in ventricular tachycardia after myocardial infarction. Under those circumstances, catheter maneuvering guided by bidirectional fluoroscopy can be difficult and time consuming and is poorly reproducible. This may play a role in the lower success rate of catheter ablation in ventricular tachycardia after myocardial infarction. The CARTO system, together with the STAR catheter, gives us the opportunity to create an accurate geometric representation of the endocardial electrophysiological recordings. Although it does not allow direct recognition of anatomic structures (such as the terminal crest or papillary muscles), the CARTO system, using endocardial recordings, allows an accurate geometric reconstruction. The CARTO system can be of help in positioning of the catheter, especially when the normal anatomy has been changed, as in myocardial infarction or corrected congenital heart disease. The effect of maneuvering the catheter can be evaluated (owing to the icon that represents the catheter tip) in relation to the electroanatomic map.

Before this system can be routinely used in the diagnosis and treatment of different arrhythmias in humans, the accuracy of the positioning of the distal segment of the catheter should be known. For this reason, we performed five ruler experiments. The purpose was to measure what the overall accuracy would be when this system was applied in the human situation. In bench testing as well as in animal testing, accuracy was very high (0.25 and 0.3 mm, respectively). The accuracy of positioning the catheter within the inferior caval vein, during which time the catheters are located within a sheath, was <1 mm. The following possible sources of error are included in this assessment: (1) system error (as in bench testing), (2) movement of the sheath within the bloodstream, (3) slippage of the catheter in the rubber stopcock in the sheath, and (4) reading errors by the investigators using the calipers. Despite these possible sources of error, accuracy is very high, especially in relation to the size (4 mm) of the tip of a standard RF ablation catheter. For obvious reasons, these measurements were made in the inferior caval vein. It is...
possible that accuracy in catheter location is not the same in a beating, non-tubelike environment such as the cardiac chambers.

We were able to reconstruct 3D electroanatomic maps during sinus rhythm as well as during different arrhythmias such as atrial and ventricular tachycardias. In sinus rhythm, the right atrium and proximal part of the coronary sinus are activated within 83.7 ms and the left atrium in 72 ms. This is in agreement with studies in the explanted human heart.\(^\text{19}\) Activation of the atria is sequential and relatively slow because in the atria, no specific conduction tissue is present. In contrast, the right as well as the left ventricular endocardium is activated within 45 ms owing to the presence of the intraventricular conduction system. Similar observations have been made using single-catheter mapping.\(^\text{20}\) Only endocardial ventricular activation can be measured, and therefore transmural conduction toward the epicardium cannot be recorded with this system.

A 3D map of an atrial tachycardia showed that activation of the atrium during tachycardia started \(\approx 1.5\) cm above the tricuspid valve. The site of origin of this arrhythmia could be well localized with this new mapping system. RF application terminated the atrial tachycardia abruptly. Although the mechanism of the arrhythmia cannot be proved with this mapping system, insight can be given in the role of anatomic structures, such as old myocardial infarction and surgical scar, in relation to arrhythmogenesis. In ventricular tachycardia after myocardial infarction, reentry is the arrhythmogenic mechanism.\(^\text{21}\) Interpretation of an early endocardial breakthrough like the one shown in the map of Figure 7 is difficult. It may be early endocardial activation over a bystander pathway, whereas the reentry circuit is located intramurally or even epicardially. Further studies must be performed to develop criteria using this new tool to identify appropriate endocardial sites to which RF energy should be applied to terminate the ventricular arrhythmia. At this time, stimulation techniques need to be performed to identify whether the earliest site of endocardial activation is indeed incorporated in the circuit.\(^\text{22}\)

An advantage of this new system is the representation of the actual catheter position within the 3D map during acquisition of the data. The effect of movement of the tip of the catheter can be evaluated immediately in relation to the 3D map. Directing the catheter to a specific site will be easier and more reproducible. This may facilitate catheter handling and may shorten procedure time. Because catheter handling is largely done without fluoroscopy, x-ray exposure for both patient and investigator should diminish considerably. However, randomized studies to compare fluoroscopy exposure with and without use of the CARTO system must be performed.

### References


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