Voltage and Activation Mapping

How the Recording Technique Affects the Outcome of Catheter Ablation Procedures in Patients With Congenital Heart Disease

Natasja M.S. de Groot, MD; Martin J. Schalij, MD; Katja Zeppenfeld, MD; Nico A. Blom, MD; Enno T. Van der Velde, PhD; Ernst E. Van der Wall, MD

Background—Endocardial mapping is mandatory before radiofrequency catheter ablation (RFCA). Mapping can be performed with either unipolar or bipolar recordings. Impact of the recording technique used was studied in patients with and without structural heart disease using the 3D electroanatomic CARTO mapping system.

Methods and Results—Patients (n=44; 16 males; age 43±16 years) referred for RFCA of atrial flutter (AFL, n=18), focal atrial tachycardia (FAT, n=4), AV nodal reentrant tachycardia (AVNRT, n=5), or scar-related atrial reentrant tachycardia (IART, n=17) were studied. Voltage and activation maps were constructed. Unipolar and bipolar voltage distribution in the different groups was studied to establish a cutoff voltage value to facilitate delineation of scar tissue. Electrograms were recorded during tachycardia (FAT: n=246, cycle length [CL]=449±35 ms; AVNRT: n=182, CL=359±47 ms; AFL: n=1164, CL=255±56 ms; IART: n=2431, CL=280±74 ms). Unipolar voltages were greater than bipolar voltages (P<0.001). Unipolar voltages ≤1.0 mV were equally distributed in both AFL and IART patients. Bipolar voltages ≥0.1 mV were only found in patients with IART, and subsequently 0.1 mV was used as the cutoff value to delineate scar tissue. No unipolar cutoff value could be established. Timing of unipolar and bipolar local activation was correlated in all patient groups.

Conclusions—The recording technique used has considerable impact on reconstruction of reentrant pathways and on the outcome of RFCA. In general, unipolar and bipolar recordings provide complementary information; however, only bipolar recordings allow voltage-based scar tissue delineation in patients with congenital heart disease. (Circulation. 2003;108:2099-2106.)

Key Words: atrial flutter ■ heart diseases ■ ablation ■ mapping ■ tachycardia

Radiofrequency catheter ablation (RFCA) is an established treatment modality for different arrhythmias.1-4 Target sites for RFCA are identified by endocardial mapping of the activation sequence, the potential distribution, and/or the morphology of the recorded signals. Especially in patients with surgically corrected congenital heart disease (CHD) and atrial reentrant arrhythmias, identification of target sites is challenging, because reentrant circuits are complex, with multiple entrances and exit sites.5 Target sites in these patients are often slow-conducting narrow isthmuses bordered by areas of scar tissue.6 Voltage criteria have been developed to allow discrimination of these slow-conducting pathways from surrounding scar tissue areas.7 The introduction of 3D mapping systems facilitated the time-consuming and difficult process of reconstruction of complex reentrant circuits.8-11 However, accurate determination of local activation time and signal amplitude is still difficult and to some degree operator dependent.12,13 Recordings are affected by different factors such as enhanced (nonuniform) anisotropy and/or the presence of scar tissue.14-16 Furthermore, the recording technique applied (unipolar or bipolar recordings), mapping catheters used (type of electrodes, electrode spacing), and filter settings of the amplifiers have considerable influence on the resulting activation and voltage maps.17-22 Most studies comparing unipolar and bipolar signals are based on animal experiments or computer simulation studies, and only a few clinical studies have been reported.13-15 We evaluated the effects of the recording technique applied on voltage and activation map reconstruction in 4 groups of patients with and without CHD, using the 3D CARTO mapping system.

Methods
Forty-four patients (aged 43±16 years; Table 1) referred for RFCA of focal atrial tachycardia (FAT), AV nodal reentrant tachycardia (AVNRT), atrial flutter (AFL), or intra-atrial reentrant tachycardia (IART; CHD patients) were included. Before ablation, patients...
TABLE 1. Patient Characteristics

<table>
<thead>
<tr>
<th></th>
<th>FAT</th>
<th>AVNRT</th>
<th>IART</th>
<th>AFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>26±14</td>
<td>44±12</td>
<td>36±9</td>
<td>64±9</td>
</tr>
<tr>
<td>Males/females</td>
<td>0/4</td>
<td>1/4</td>
<td>5/12</td>
<td>10/8</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Coarctation of the aorta</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Atrial septal defect</td>
<td>0 0 3 0</td>
<td>0 0 3 0</td>
<td>0 0 3 0</td>
<td>0 0 3 0</td>
</tr>
<tr>
<td>AV septal defect</td>
<td>0 0 1 0</td>
<td>0 0 1 0</td>
<td>0 0 1 0</td>
<td>0 0 1 0</td>
</tr>
<tr>
<td>Transposition of great arteries</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>Tricuspid atresia</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
</tr>
</tbody>
</table>

Values are number of patients unless otherwise indicated.

underwent cardiac evaluation, which included 24-hour Holter monitoring, echocardiography, and a diagnostic electrophysiological study. Antiarrhythmic drugs were discontinued at least 3 days before ablation.

Mapping Procedure

Mapping was performed with the CARTO electroanatomic mapping system (Biosense-Webster). A 7F Navi-Star catheter (4-mm tip, 2 bipolar electrode pairs, interelectrode distance 2 mm; Biosense-Webster) was used as the mapping/ablation catheter. The catheter was dragged over the endocardial surface to record electrograms at different sites and to simultaneously determine the shape and volume of the atrium. Complete right atrial endocardial maps were obtained in all patients to ensure reconstruction of detailed voltage-distribution curves. A recording was accepted and integrated in an activation or voltage map when the variability in cycle length (CL), local activation time stability, and maximum beat-to-beat difference of the location of the catheter were respectively <2%, <3 ms, and <4 mm. These parameters, combined with impedance measurements, were used to exclude signals with low amplitudes due to poor contact of the tip of the catheter with the endocardium. Unipolar and bipolar electrograms were recorded simultaneously. Bipolar electrograms were constructed by real-time subtraction of 2 unipolar electrograms (tip and distal ring electrode). All signals were filtered at 10 to 400 Hz. Wilson’s central terminal served as the indifferent electrode for unipolar recordings. A quadrripolar 6F reference catheter (Biosense-Webster) was positioned in the right atrium.

Local activation time was determined automatically by marking the maximum negative slope of the intrinsic deflection (unipolar recording) or maximum amplitude (bipolar recording). Markings were adjusted manually if necessary. In case of multiple deflections, the largest deflection was marked as the moment of local activation. Color-coded activation maps were reconstructed online and superimposed on the anatomy. The peak-to-peak amplitude of unipolar and bipolar electrograms was measured automatically and used to construct online color-coded unipolar and bipolar voltage maps. In case of fragmented electrograms, the peak-to-peak amplitude of the largest deflection was measured. Programmed electrical stimulation applying up to 3 extrastimuli (twice diastolic threshold) was performed with a constant current stimulator (Medtronic).

Radiofrequency Ablation

After mapping, a radiofrequency ablation procedure was performed. Radiofrequency current was applied for 60 seconds (maximum tip temperature set at 70°C, maximum output 50 W). Success was defined by (1) noninducibility of the clinical arrhythmia after the procedure, (2) establishment of a line of conduction block over the cavo-tricuspid isthmus (AFL patients), or (3) establishment of a line of conduction block between 2 anatomic boundaries (eg, scar areas in IART patients).

Postprocedure and Follow-Up

After the procedure, patients were heparinized for 24 hours. An echocardiogram and a chest radiograph were obtained <24 hours after the procedure. Aspirin (80 mg/d) was administered for 3 months.

Statistical Analysis

All data are expressed as mean±SD. Statistical significance was defined as P<0.05. The Pearson correlation coefficient was used to determine the correlation between (1) the local activation time of unipolar and bipolar electrograms and (2) the voltage of unipolar and bipolar electrograms. Differences between unipolar and bipolar electrogram voltages were analyzed with the Wilcoxon signed-rank test.

TABLE 2. Voltage Characteristics of Unipolar and Bipolar Electrograms

<table>
<thead>
<tr>
<th></th>
<th>FAT</th>
<th>AVNRT</th>
<th>IART</th>
<th>AFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unipolar electrograms, n</td>
<td>246</td>
<td>182</td>
<td>2431</td>
<td>1164</td>
</tr>
<tr>
<td>Mean±SD, mV</td>
<td>3.1±1.4</td>
<td>3.1±1.2</td>
<td>2.1±1.9</td>
<td>2.5±1.6</td>
</tr>
<tr>
<td>Minimum, mV</td>
<td>2.0</td>
<td>1.28</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>Maximum, mV</td>
<td>8.9</td>
<td>9.8</td>
<td>9.4</td>
<td>9.5</td>
</tr>
<tr>
<td>Bipolar electrograms, n</td>
<td>246</td>
<td>182</td>
<td>2431</td>
<td>1164</td>
</tr>
<tr>
<td>Mean±SD, mV</td>
<td>1.8±1.6</td>
<td>1.6±1.1</td>
<td>0.9±1.1</td>
<td>1.4±1.5</td>
</tr>
<tr>
<td>Minimum, mV</td>
<td>0.12</td>
<td>0.22</td>
<td>0.03</td>
<td>0.11</td>
</tr>
<tr>
<td>Maximum, mV</td>
<td>7.8</td>
<td>9.4</td>
<td>4.6</td>
<td>8.9</td>
</tr>
<tr>
<td>R value</td>
<td>P&lt;0.001</td>
<td>P&lt;0.001</td>
<td>P&lt;0.001</td>
<td>P&lt;0.001</td>
</tr>
<tr>
<td>R (voltage)</td>
<td>0.73†</td>
<td>0.73†</td>
<td>0.65†</td>
<td>0.67†</td>
</tr>
<tr>
<td>R (LAT)</td>
<td>0.42†</td>
<td>0.54†</td>
<td>0.14*</td>
<td>0.31*</td>
</tr>
<tr>
<td>CL, ms</td>
<td>449±35</td>
<td>359±47</td>
<td>280±74</td>
<td>255±56</td>
</tr>
</tbody>
</table>

LAT indicates local activation time.

P values correspond to mean amplitude. Pearson correlation coefficients are for unipolar vs bipolar voltage (R [voltage]) and unipolar vs bipolar LAT (R [LAT]).

*P<0.01; †P<0.001.
Results

All IART patients (n = 17) had surgically corrected CHD (Table 1). Two of 18 AFL patients had a structural heart disease. No FAT (n = 4) or AVNRT (n = 5) patients had structural heart disease. Unipolar and bipolar electrograms were recorded during FAT (61 ± 26 signals/patient, CL = 449 ± 35 ms), AVNRT (36 ± 17 signals/patient, CL = 359 ± 47 ms), AFL (65 ± 36 signals/patient, CL = 255 ± 56 ms), and IART (143 ± 89 signals/patient, CL = 280 ± 74 ms).

Voltage Distribution

Although the bipolar voltage was less than the unipolar voltage (P < 0.001), a significant correlation between unipolar and bipolar recordings was found in all groups (Table 2). During FAT and AVNRT (Figure 1A and 1B), all unipolar electrograms had an amplitude ≥ 1.0 mV. However, during AFL and IART (Figure 1C and 1D), a large number of unipolar signals were ≤ 1.0 mV (AFL 19%, IART 35%; Figure 1E and 1F). Thus, despite the absence of detectable structural heart disease in most AFL patients, the unipolar voltage distribution was different from the unipolar voltage distribution recorded in AVNRT and FAT patients and mimicked the voltage distribution found in IART patients.

The majority (> 60%) of bipolar electrograms recorded in patients with FAT and AVNRT were > 1.0 mV (Figure 2A and 2B), whereas during IART and AFL (Figure 2C and 2D), the majority of signals were ≤ 1.0 mV (IART 74%, AFL 51%). Low voltages (≤ 1.0 mV) during FAT, AVNRT, and AFL (Figure 2E, 2F, and 2G) were equally distributed, and no signals with an amplitude ≤ 0.1 mV were recorded in any of these patients. In CHD patients (Figure 2H), 16% of the signals had an amplitude ≤ 0.1 mV.

Voltage Maps and Scar Tissue Delineation

From the bipolar voltage distribution curves, it is clear that in normal hearts, no bipolar signals with a voltage ≤ 0.1 mV were recorded. In contrast, in CHD patients, 16% of the signals were ≤ 0.1 mV. Therefore, and based on previous studies, a cutoff value of 0.1 mV was taken to discriminate scar tissue from viable myocardium.7 From the unipolar voltage-distribution curves, it appeared that it was not possible to depict a cutoff value to discriminate scar from conducting tissue. Therefore, scar areas were delineated based on the bipolar cutoff value of 0.1 mV and on bipolar recordings only. After scar tissue mapping, scar areas were superimposed on the anatomy. Bipolar and unipolar voltage maps were constructed with the same

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**Figure 1.** Frequency distribution of unipolar electrograms. Electrograms with amplitude < 1.0 mV were only recorded in patients with AFL and IART. A, FAT; B, AVNRT; C and E, AFL; D and F, IART.
scar maps. In Figure 3, 4 pairs of corresponding unipolar (left) and bipolar (right) voltage maps recorded during FAT, AVNRT, AFL, and IART are shown. Large areas of scar (gray areas) were recorded during IART only.

**Activation Mapping**

In general, during FAT and AVNRT, fragmentation was minimal, and the local activation time could be determined automatically without manual adjustments. However, during AFL and IART, determination of local activation time was hampered by enhanced fragmentation, recorded within large areas of the endocardial surface. In case of low-amplitude fragmented signals, >85% of the automatic markings were not accurate, which necessitated manual adjustments. Consequently, differences in timing of unipolar and bipolar activation occurred. Despite these problems, a weak but significant correlation between unipolar and bipolar activation times was found in all patient groups (Table 2). Because most signals during FAT did not show fragmentation, only minimal differences between unipolar and bipolar activation maps were found (Figure 4, left panels). Also during AFL (Figure 4, right panels), most sites only showed minimal differences.

**Figure 2.** Frequency distribution of bipolar electrograms. Bipolar electrograms with amplitudes ≤0.1 mV were only recorded in patients with IART. A and C, FAT; B and F, AVNRT; C and G, AFL; D and H, IART.

"scar" maps. In Figure 3, 4 pairs of corresponding unipolar (left) and bipolar (right) voltage maps recorded during FAT, AVNRT, AFL, and IART are shown. Large areas of scar (gray areas) were recorded during IART only.

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In general, during FAT and AVNRT, fragmentation was minimal, and the local activation time could be determined automatically without manual adjustments. However, during AFL and IART, determination of local activation time was hampered by enhanced fragmentation, recorded within large areas of the endocardial surface. In case of low-amplitude fragmented signals, >85% of the automatic markings were not accurate, which necessitated manual adjustments. Consequently, differences in timing of unipolar and bipolar activation occurred. Despite these problems, a weak but significant correlation between unipolar and bipolar activation times was found in all patient groups (Table 2). Because most signals during FAT did not show fragmentation, only minimal differences between unipolar and bipolar activation maps were found (Figure 4, left panels). Also during AFL (Figure 4, right panels), most sites only showed minimal differences.
in timing between unipolar and bipolar recordings. However, increased fragmentation in the area near the cavo-tricuspid isthmus did result in differences between the unipolar and bipolar activation maps. During IART (Figure 5), differences between unipolar and bipolar activation maps due to enhanced fragmentation were even more prominent. Delineation of scar (gray areas) when a cutoff value of 0.1 mV was used resulted in a few large areas of scar tissue (bipolar activation map). These scar zones were superimposed on the anatomy and also used during analysis of the unipolar activation map (red encircled areas). Ablation aimed at connecting the 2 scar areas resulted in termination of the arrhythmia (white line). Although the unipolar and bipolar map look similar at some sites, differences between the unipolar and bipolar activation time of 20 ms (red dots) hampered detailed reconstruction of the reentrant pathway. In this case, the reentrant pathway was reconstructed with only bipolar electrograms, because they were less distorted by far-field electrical activity.

Far-field electrical events may impede precise measurement of activation times, especially in low-amplitude areas during IART (Figure 6). In this example (patient after Fontan procedure), the underlying mechanism was a figure 8 type of reentry. In relatively normal areas, both unipolar and bipolar recordings can be used to map the spread of activation (panels 2 and 3). However, in the low-amplitude areas (panel 1), far-field signals were present, which made identification of the low-amplitude local unipolar potentials uncertain, whereas the bipolar signals could still be used. RFCA aimed at connecting the 2 scar areas resulted in termination of the arrhythmia (dotted line).

Outcome of the RF Procedure
RFCA was successful (success defined as noninducibility of the clinical arrhythmia after ablation) in all AVNRT and FAT patients and in 85% and 83% of the IART and AFL patients, respectively. Complications were not observed. During follow-up (18±6 months), 3 IART patients (18%) and 2 AFL patients (11%) had a recurrence.

Discussion
We demonstrated significant differences between simultaneously recorded unipolar and bipolar signals and consequently between unipolar and bipolar voltage and activation maps in CHD patients. These differences have an effect not only on reentrant pathway reconstruction but also on selection of radiofrequency target sites.

Unipolar and Bipolar Electrograms
The shape and amplitude of unipolar and bipolar electrograms and consequently the reconstructed endocardial activation maps are influenced by electrophysiological and structural characteristics of the myocardial tissue involved. Surprisingly, in this era of catheter ablation and detailed endocardial mapping, only a few clinical studies have addressed the issue of signal morphology and analysis. Unipolar recordings offer some advantages compared
with bipolar recordings (because they are the subtraction of 2 unipolar signals); for example, unipolar signals may provide essential information about the direction of impulse propagation, which may be helpful in localizing exit points of reentrant circuits and precise localization of accessory pathways, among other things.26 However, because unipolar recordings are more susceptible to noise and surrounding influences, recording of acceptable unipolar signals is technically challenging.13,23,24 Additionally, as shown (Figure 6), unipolar recordings, especially in case of fragmented low-amplitude signals, may be distorted or obscured by far-field electrical activity. Bipolar recordings, on the other hand, are affected by electrode configuration, distance between the recording electrodes, and the direction of the wave front with respect to the electrode orientation. Furthermore, criteria for marking the moment of local activation of complex bipolar electrograms are less well defined.25,26 It is therefore not surprising that reconstruction of endocardial activation patterns depends on the recording technique used and that unipolar and bipolar recordings provide complementary information.

Voltage Maps
From computer simulation and experimental studies, it is well known that unipolar voltages are larger than bipolar voltages.13,17 In line with this perception, we demonstrated that unipolar signal amplitudes were higher than the simultaneously recorded bipolar signal in all patient groups. From the voltage-distribution curves, a significant difference between patients with and without structural heart disease (eg, CHD) could be detected. In patients without structural heart disease, the signal amplitudes were significantly larger than those recorded in CHD patients. The amplitude of a unipolar signal (and consequently the amplitude of the derived bipolar signal) is determined by the volume of the cardiac tissue that surrounds the recording electrode activated at the same time. In normal atrial myocardium with intact electrical coupling and normal conduction characteristics, large areas will be activated simultaneously, and the amplitude of the recorded signals will be relatively large. However, if myocardial fibers become separated (eg, because of aging or in diseased myocardium), conduction velocity will decrease, and atrial fibers will be activated increasingly asynchronously.16,18 In other words, only small areas will be activated at the same time, and the amplitude of the recorded signals will decrease. This explains the voltage distribution found in CHD patients. Surprisingly, a high number of low-voltage electrograms were also recorded in AFL patients despite the absence of detectable structural heart disease in the majority of these patients. These findings support observations by others demonstrating increased fragmentation in AFL patients and suggest that increased fibrosis results in abnormal electrical characteristics.20–22

Figure 4. Unipolar and bipolar activation maps constructed during FAT (left, CL=390 ms) and AFL (right, CL=250 ms) in anteroposterior and caudal view, respectively. Examples of electrograms are shown outside activation maps. Differences in local activation time were mainly present in areas from which fragmented electrograms were recorded. TV indicates tricuspid valve; ICV, inferior caval vein.
Scar Tissue Delineation, Activation Time, and Activation Maps

Although debate continues about scar tissue cutoff values to be used in CHD patients, and only limited data are available, we demonstrated that owing to voltage differences between unipolar and bipolar signals, it is not justified to use a single cutoff value for unipolar and bipolar signals, because this may have dramatic effects on the reconstructed activation maps. Because there is no clear distinction between “normal” and scar tissue in patients with and without structural heart disease in the low-voltage areas, it will not be possible to determine a single unipolar cutoff value. On the other hand, when we studied the bipolar voltage distribution of signals \( \leq 1.0 \text{ mV} \), it appeared that only in structural heart disease (CHD) did a significant number of signals have an amplitude of \( \leq 0.1 \text{ mV} \). Because signals with \( \leq 0.1 \text{ mV} \) were found in none of the other patient groups, it seems justified to depict 0.1 mV as the cutoff value to delineate scar tissue.

Determination of local activation times depends on signal quality and signal characteristics. In case of high-amplitude signals, determination of the local activation time is relatively easy. This is supported by the present results showing that in patients with normal hearts, automatic marking of both unipolar and bipolar markings required almost no manual adjustments (FAT 98%, AVNRT 95%, AFL 67%), and only minimal differences were detected between unipolar and bipolar activation maps.

However, when low-amplitude fragmented signals prevailed (CHD patients), application of automatic marking algorithms was not possible. From animal studies, it is known that the maximum negative derivative of fragmented unipolar electrograms does not always reflect the moment of activation of cells beneath the recording electrode but may reflect activation of bundles at a distance. Hence, assignment of a local activation time to fragmented unipolar and corresponding bipolar electrograms is subject to errors. Moreover, it is still unknown which specific component of fragmented bipolar electrograms is related to the local activation time.25

Given the previous considerations, it is understandable that only minimal differences will be found when unipolar and bipolar activation maps recorded in patients without structural heart disease are compared. In patients after surgery, however, significant differences can be expected.6,7,9,13

Clinical Implications

Reconstruction of reentrant circuits before ablation depends on meticulous analysis of acquired data. It is therefore not possible to simply state superiority of unipolar or bipolar recordings; the characteristics of both electrode configurations provide complementary information and should be used in combination with voltage and activation mapping. Unipolar recordings provide essential information about the direction of impulse propagation, whereas bipolar signals allow voltage-based scar tissue delineation.

Study Limitations

This study is limited by the fact that only 1 specific catheter type and fixed system settings were used. Furthermore, the interoperator/interobserver variability was not studied, which may have affected the manual marking adjustments. Complete right atrial endocardial activation maps were obtained in all patients to assess reliable voltage-distribution curves. Especially in the CHD patients, some overestimation of the number of low-voltage signals may have occurred. This had no effect on the determination of the scar tissue cutoff value, because this value was based on the comparison of voltages found in CHD patients and the other patient groups and not on the frequency distribution. However, we realize that because no sites \( < 0.1 \text{ mV} \) were found in normal hearts, the cutoff value may be a conservative estimate. Furthermore, the cutoff value used to delineate scar tissue is an electrogram definition and is not based on histological studies.
Conclusions
Significant differences exist between simultaneously recorded unipolar and bipolar signals. These differences have considerable impact on reconstruction of complex reentrant pathways and consequently on the outcome of RFCA procedures. In general, unipolar and bipolar recordings provide complementary information; however, only bipolar recordings allow voltage-based scar tissue delineation in CHD patients.

References
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