LocaLisa

New Technique for Real-Time 3-Dimensional Localization of Regular Intracardiac Electrodes

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Background—Estimation of the 3-dimensional (3D) position of ablation electrodes from fluoroscopic images is inadequate if a systematic lesion pattern is required in the treatment of complex arrhythmogenic substrates.

Methods and Results—We developed a new technique for online 3D localization of intracardiac electrodes. Regular catheter electrodes are used as sensors for a high-frequency transthoracic electrical field, which is applied via standard skin electrodes. We investigated localization accuracy within the right atrium, right ventricle, and left ventricle by comparing measured and true interelectrode distances of a decapolar catheter. Long-term stability was analyzed by localization of the most proximal His bundle before and after slow pathway ablation. Electrogram recordings were unaffected by the applied electrical field. Localization data from 3 catheter positions, widely distributed within the right atrium, right ventricle, or left ventricle, were analyzed in 10 patients per group. The relationship between measured and true electrode positions was highly linear, with an average correlation coefficient of 0.996, 0.997, and 0.999 for the right atrium, right ventricle, and left ventricle, respectively. Localization accuracy was better than 2 mm, with an additional scaling error of 8% to 14%. After 2 hours, localization of the proximal His bundle was reproducible within 1.4 ± 1.1 mm.

Conclusions—This new technique enables accurate and reproducible real-time localization of electrode positions in cardiac mapping and ablation procedures. Its application does not distort the quality of electrograms and can be applied to any electrode catheter. (Circulation. 1999;99:1312-1317.)

Key Words: mapping • catheter ablation • electrophysiology

The position of intracardiac catheter electrodes during electrophysiological procedures is usually estimated from biplane fluoroscopic images. This method does allow for a rough estimation of electrode positions but is unsatisfactory for detailed catheter mapping and for the more advanced ablation techniques that are presently applied to ablate complex arrhythmogenic substrates. In patients with atrial flutter, for example, the reentrant circuit can be eliminated by a linear array of radiofrequency (RF) energy applications that create a continuous line of block in the lower right atrial (RA) isthmus. Similar techniques have been investigated for the treatment of atrial fibrillation.

Recently, a magnetic, nonfluoroscopic, catheter localization method was introduced. Its major limitation, however, is the mandatory use of a specific catheter design, which excludes other catheter types and brands. Moreover, multiple electrodes on the same catheter or electrodes on complex catheters cannot be localized.

We developed a new technique (LocaLisa) for real-time 3-dimensional (3D) localization of intracardiac catheter electrodes. This method uses an externally applied electrical field that is detected via standard catheter electrodes. The present study was performed to investigate the accuracy and limitations of this new electrode localization technique.

Methods

When an electrical current is externally applied through the thorax, a voltage drop occurs across internal organs like the heart (Figure 1). The resulting voltage can be recorded via standard catheter electrodes and potentially can be used to determine electrode position.

To apply this concept to catheter mapping and ablation procedures, the following requirements must be met: (1) the method must be applied in 3 orthogonal directions; (2) the externally applied electrical field must be harmless and must not interfere with electro(cardio)grams; (3) cyclic variations due to cardiac contraction and respiration must be offset; (4) the localization method must be stable throughout a catheterization procedure; and (5) the system must be calibrated to translate changes in recorded voltages into changes in electrode position.

Analogous to the Frank lead system, 3 skin-electrode pairs were used to send 3 small, 1-mA currents through the thorax in 3 orthogonal directions, with slightly different frequencies of ~30 kHz.
used for each direction (Figure 2). Standard surface ECG electrodes were placed at the right and left midaxillary lines at the fourth intercostal space (V4) level (X field) and at the left shoulder and left leg (Y field). Two 10×15-cm skin patches, 1 anterior above the heart at the V2 position and the other posterior under the heart on the back, were used to create the Z field. Both latter electrodes were chosen to be relatively large, because their proximity to the heart was expected to create an otherwise too inhomogeneous electrical field. The posterior skin patch simultaneously served as the return electrode for RF ablation. The 30-kHz signal was not expected to interfere with electrophysiological recordings, and the 1-mA current level was in accordance with international safety standards.13

The mixture of 30-kHz signals, recorded from each catheter electrode, was digitally separated to measure the amplitude of each of the 3 frequency components. The 3 electrical field strengths were calculated automatically by use of the difference in amplitudes measured from neighboring electrode pairs with a known interelectrode distance for ≥3 different spatial orientations of that dipole. We then calculated the 3D position of each electrode by dividing each of the 3 amplitudes (V) by the corresponding electrical field strength (V/cm).

The electrode positions were averaged over 1 or 2 seconds to reduce cyclic cardiac variations. Respiratory variations are too slow to be eliminated by averaging without compromising the real-time nature of the localization method, and their effect on localization accuracy is part of this study.

Device Specifications

The battery-powered LocaLisa system was designed and built at our institute. By use of the above-mentioned orthogonal lead configuration, 3 independent alternating currents of 1 mA were delivered through the patient’s chest, with 30.27 kHz, 30.70 kHz, and 31.15 kHz used for the X, Y, and Z directions, respectively (Figure 2). The system had 2 input amplifiers for measuring the resulting signal on 2 mapping catheter electrodes relative to a stable skin or catheter reference electrode. The amplitudes of each of the 3 frequency components were optically transmitted to a Macintosh computer. A custom-designed software application provided moving-average filtering, calibration, and real-time display of the position of the distal portion of the mapping catheter using 2 of its electrodes (Figure 3).

Study Protocol 1

All catheterization procedures were performed with the patients in the fasting, nonsedated state. The first study protocol was approved by our institution’s ethics committee, and informed consent was obtained from each patient. In 30 patients, a deflectable decapolar electrode catheter (Marinr, Medtronic CardioRhythm) was placed in a stable position within either the RA, right ventricle (RV), or left ventricle (LV) in 10 different patients for each group during the 30-minute observation period after a standard catheter ablation procedure. Sequentially, each of the 10 electrodes was connected to the LocaLisa system. Measurements were repeated at 2 other stable catheter positions within the same chamber. The 3 catheter positions were chosen such that the electrode positions covered a major portion of the cardiac chamber.

Total interelectrode spacing was 53.5 mm for the RA and RV catheters and 54 mm for the longer LV catheters, and all electrode positions and interelectrode distances were defined by use of the geometric center of each electrode.

Study Protocol 2

The magnitude of cyclic variations in the position of a fluoroscopically and electrographically stable catheter-tip electrode was measured in 30 patients in whom the LocaLisa system had been used clinically during catheter mapping and ablation. Measurements were performed within the RA, RV, and LV in 10 different patients per group. With a stable catheter position, both this tip electrode and the
tip electrode of a coronary sinus (CS) catheter were connected to the LocaLisa system with a right leg electrode used as a reference. Measurements were taken once per second for 20 to 30 seconds.

**Study Protocol 3**

Long-term stability of the LocaLisa system was determined in 14 patients with AV nodal reentrant tachycardia by use of a reference electrode in the CS or one of its side branches. The most proximal His bundle recording site, characterized by a bipolar His bundle deflection <50 μV and a negative deflection on the distal unipolar electrogram only, was determined before and after posterior AV nodal modification.

**Calibration**

In the first study, the 27 sets of interelectrode distances and corresponding voltage amplitude differences that were obtained with the 3 catheter positions were used for automatic calibration. The 3 calculated field strengths (in mV/cm) thus reflect the average values within the area covered by all 3 catheter positions.

In studies 2 and 3, calibration was performed automatically with the data obtained from the tip and the fourth (ring) electrodes of the mapping catheter at multiple catheter positions and orientations obtained during catheterization in the same chamber.

**Data Analysis**

With the decapolar catheters, positions along the catheter shaft were calculated by summation of interelectrode distances. The accuracy and linearity of the LocaLisa system were analyzed by comparison of measured and true positions of the 10 electrodes for each catheter position. With linear regression analysis, the slope of the regression line between measured and true electrode positions, the correlation coefficient, and the residual SD around the regression line were calculated.

In study 2, the SDs of the recorded voltages (in 3 directions), measured at 1-second intervals, were divided by the corresponding field strength values to obtain the SD of the variations in electrode position.

In study 3, reproducibility of the localization method was determined by measurement of the difference between the 2 proximal His bundle positions, measured at the beginning and end of the ablation procedure.

All values are expressed as mean±SD.

**Results**

The 3 transthoracic currents did not create any patient discomfort and did not interfere with even the most sensitive unipolar and bipolar electrograms (unipolar: 1 mV/cm, 0.1 to 500 Hz; bipolar: 0.25 mV/cm, 50 to 500 Hz). The LocaLisa amplifiers were connected to intracardiac electrodes in parallel with the standard electrogram amplifiers (Figure 2); these electrograms also remained unaffected.

In study 1, only 2 stable catheter positions could be obtained in 2 patients of each ventricular group. Thus, in 30 patients, data of 30 RA, 28 RV, and 28 LV catheter positions were analyzed.

Measured interelectrode distances were plotted against true distances for all catheter positions in each patient (Figure 4). The relationship between measured and true electrode distances was highly linear for all catheter positions, with average correlation coefficients between 0.996 and 0.999 (Table 1). This suggests that the electrical fields were very homogeneous within the 53.5 or 54 mm covered by the catheter electrodes. The average slopes of the regression lines were 0.99, 0.95, and 0.97, and the corresponding average residual SDs around the regression line were 1.7, 1.3, and 1 mm for the RA, RV, and LV, respectively (Table 1).

The magnitude of cyclic cardiac and respiratory variations in electrode position was measured at fluoroscopically and electrographically stable RA, RV, and LV catheter positions in 10 patients for each group (Table 2). When a 2-second

<p>| Table 1. Localization Accuracy With Decapolar Catheters |
|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>RA</th>
<th>RV</th>
<th>LV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients, n</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Positions per patient, n</td>
<td>3</td>
<td>2.8</td>
</tr>
<tr>
<td>Area size, mm</td>
<td>53.5</td>
<td>53.5</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>0.996±0.004</td>
<td>0.997±0.003</td>
</tr>
<tr>
<td>Residual SD, mm</td>
<td>1.7±0.8</td>
<td>1.3±0.7</td>
</tr>
<tr>
<td>Slope</td>
<td>0.99±0.14</td>
<td>0.95±0.10</td>
</tr>
</tbody>
</table>

Data obtained from decapolar catheters in 3 positions in the RA and RV or LV. Extremely high correlation coefficients were found between calculated and true electrode positions along the shaft of the catheter. The residual SD is the SD of measured electrode positions around the regression line. The slope represents the scaling factor between measured and true interelectrode distances.
filter and a right-leg reference electrode were used, the average SD of electrode position was 1.3, 1.8, and 1.5 mm for the RA, RV, and LV, respectively. The use of a CS reference electrode resulted in significantly lower values of 0.8, 1.1, and 0.8 mm, respectively. The low frequency and cyclic nature of the electrode movements suggested that these variations were predominantly caused by respiration.

We investigated the long-term stability of the LocaLisa system by comparing the most proximal His bundle recording site before and after slow pathway ablation in 14 patients with AV nodal reentrant tachycardia. Early in the study, the CS reference catheter in 2 patients migrated further into the vein during the course of the procedure, as was obvious from fluoroscopic images. In subsequent patients, we attempted to position the CS reference catheter in the middle cardiac vein or a more distal branch to ensure a stable position. Dislocation, however, also occurred in one of these patients. Data of these 3 patients were excluded from analysis. In the remaining 11 patients, the average distance between the preablation and postablation proximal His bundle location was 1.4±1.1 mm. There was no systematic drift in the system: the average change in position was +0.2±1.7 mm for the X, -0.1±0.3 mm for the Y, and +0.2±0.6 mm for the Z direction. The time interval between the 2 measurements was 128±82 minutes.

**Discussion**

In these studies, we analyzed the feasibility and accuracy of a new electrical localization technique for intracardiac catheter electrodes. System accuracy was evaluated by use of the known interelectrode distances of a standard decapolar electrode catheter. Measurement of interelectrode distances over 54 mm was extremely linear within all 3 cardiac chambers examined. The method does not require specially designed catheters because it uses standard catheter electrodes to measure an externally applied electrical field. This allows freedom of catheter choice and catheter exchange during the procedure. Moreover, the technique can be applied to complex catheter designs such as multielectrode catheters, irrigated electrode catheters, and basket catheters.\(^{14-17}\) After catheter removal, another ablation catheter can be guided to the same locations, eg, to complete a line of block or to ablate at or near a previously identified site. For those applications, localization accuracy is pivotal.

**Accuracy**

Electrode localization with the LocaLisa system is potentially affected by respiratory and cardiac movements, inhomogeneities of the externally applied electrical field, and drift.

**Respiratory and Cardiac Movements**

In this study, we used a low-pass moving-average filter to eliminate cyclic cardiac variations in the measured electrical signals. The 2-second averaging period was felt to be an acceptable compromise between localization accuracy and speed of response. We observed relatively small cyclic variations in electrode position of 1 to 2 mm (Table 2), which explains the similar residual SD around the regression line measured in the first study. Averaging over a longer time period not only would have reduced these variations but also would have slowed down the response of the system to a sudden shift in catheter position (Figure 5). The results of study 2 suggest that the use of a CS instead of a skin reference electrode would have reduced these variations by a factor of \(\approx 2\) (Table 2). Alternatively, this would allow for a reduction

<table>
<thead>
<tr>
<th>Reference</th>
<th>Right Leg</th>
<th>CS 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD, in millimeters.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RA</td>
<td>RV</td>
<td>LV</td>
</tr>
<tr>
<td>1 s</td>
<td>1.7±0.8</td>
<td>1.1±0.4</td>
</tr>
<tr>
<td>2 s</td>
<td>1.3±0.7</td>
<td>0.8±0.3</td>
</tr>
</tbody>
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SD of fluoroscopically and electrographically stable electrode positions measured at 1-second intervals for 20 to 30 seconds in the RA, RV, and LV or 10 patients for each group with a 1 and 2-second moving average/second filter. For each electrode position, measurements were performed simultaneously relative to a right leg and to the distal electrode of a CS catheter. Differences in measured SD obtained with the 2 different reference electrodes and with the 2 filter settings were all statistically significant (paired t tests). For all 3 chambers, differences in SD between the 2 filter–right-leg reference setting and the 1-second filter–CS/second reference setting were statistically not significant (paired t tests: \(P=0.22, 0.19, \text{and } 0.10\) for the RA, RV, and LV, respectively). Values are mean±SD, in millimeters.
of the averaging duration to 1 second and thus for a faster response of the system to catheter movements (Figure 5).

Inhomogeneity of the Electrical Field
Calibration with the data from all 30 electrodes, thus assuming a homogeneous 3D electrical field within the entire cavity, caused an 8% to 14% scaling error (Table 1). This error must be explained by inhomogeneity of the electrical field. This is of little clinical relevance given that the region of interest is usually limited to a few centimeters in cross section in which the scaling error will affect all sites similarly. Moreover, all electrode positions will remain uniquely identifiable with an error of 1 to 2 mm, which is acceptable given the size of regular mapping and ablation electrodes and RF lesions.

Long-Term Stability
Measurement of the most proximal His bundle position revealed very good reproducibility and stability of the localization method. However, stability of the spatial reference catheter remains critically important for any localization system. Future expansion of the LocaLisa system to include more input channels will allow for a retrospective switch to another reference electrode in case of dislocation. In critical cases such as catheter ablation for ventricular tachycardia, we have been using a 2F temporary pacing wire with active fixation in the RV as a reference (model 6416, Medtronic CardioRhythm).

Clinical Implications
Except for the extra skin electrodes, the use of the LocaLisa system only requires a mouse click or key stroke to mark successive electrode positions. Since the completion of the present study, we have used the device in >250 catheter mapping and ablation procedures for various types of supraventricular and ventricular tachyarrhythmias presently amenable to catheter ablation. Different types and brands of standard steerable electrode catheters were used with frequent catheter exchange during procedures. In the ablation of accessory AV pathways,2,15,18–21 sequential marking of mapping/ablation sites often revealed spatial incompleteness in areas that were difficult to access. Sites with transient block targeted the site of successful ablation. Facilitation of repositioning of the ablation electrode demonstrated its value after incomplete ablations caused by catheter dislocation or early coagulum formation, especially if these ablations had caused (transient?) interruption of the accessory pathway. With atrial and ventricular tachycardias, extra RF pulses could be applied closely around an apparently successful ablation site to ensure elimination of the arrhythmogenic area.22,23

The technique has been very helpful for a systematic, anatomically guided approach in the treatment of AV nodal reentrant tachycardia,24–26 avoiding repeated ablations at the same location and ablations in close proximity to the most proximal His bundle recording site. In patients with atrial flutter, we use the system to delineate the region of interest (by identifying His, CS ostium, and tricuspid annulus) and to create a line of block in the lower RA isthmus (Figure 3).

The current LocaLisa system can only measure the position of 2 electrodes simultaneously. With more input channels, the system would allow for real-time imaging of the electrode positions of more intracardiac catheters. This would give the catheterizing cardiologist a better perspective of the position of the mapping catheter relative to cardiac anatomic structures and allow for a substantial reduction in fluoroscopy time. More input channels would also allow for the use of more than one reference electrode, as discussed above.

Clinically, this new technique is and will be combined with RF delivery via the same electrode. With the first-generation device, the application of RF energy transiently disabled localization of the ablation electrode. Recently, dedicated filtering techniques have enabled continuous electrode localization during RF delivery.

Limitations
The accuracy of this localization technique has not yet been investigated in the left atrial cavity. Transseptal punctures are not often performed at our center, and 3 spatially different left atrial catheter positions are very difficult to obtain via a retrograde aortic approach. There is, however, little reason to expect less favorable results in the left atrium. On the contrary, its more central position within the thorax may be expected to result in a more homogeneous electrical field and an even better localization accuracy than in the other 3 chambers.

Conclusions
The LocaLisa technique allows for real-time, nonfluoroscopic, 3D visualization of standard intracardiac catheter electrodes and is sufficiently accurate for detailed catheter mapping and the creation of linear or complex RF lesion patterns. Localization accuracy within the RA and ventricular cavities is on the order of 1 to 2 mm. The gradient of the electrical field may cause an additional scaling error of 8% to 14% within an entire cardiac cavity. Given a stable reference electrode, the localization method is reliable during catheterization procedures that last several hours.

Acknowledgments
The authors gratefully acknowledge the dedicated assistance of the Catheterization Laboratory of the University Hospital Utrecht. The LocaLisa system was developed at the Department of Biomedical Engineering of the University Hospital Utrecht and financed by the Bakken Research Center, Maastricht, The Netherlands.

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Circulation. 1999;99:1312-1317
doi: 10.1161/01.CIR.99.10.1312

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