Anatomic Stereotactic Catheter Ablation on Three-Dimensional Magnetic Resonance Images in Real Time

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Background—Targets for radiofrequency (RF) ablation of atrial fibrillation, atrial flutter, and nonidiopathic ventricular tachycardia are increasingly being selected on the basis of anatomic considerations. Because fluoroscopy provides only limited information about the relationship between catheter positions and cardiac structures and is associated with radiation risk, other approaches to mapping may be beneficial.

Methods and Results—An electromagnetic catheter positioning system was superimposed on 3D MR images using fiducial markers. This allowed the dynamic display of the catheter position on the true anatomy of previously acquired MR images in real time. In vitro accuracy and precision during catheter navigation were assessed in a phantom model and were 1.11±0.06 and 0.30±0.07 mm (mean±SEM), respectively. Left and right heart catheterization was performed in 7 swine without the use of fluoroscopy, yielding an in vivo accuracy and precision of 2.74±0.52 and 1.97±0.44 mm, respectively. To assess the reproducibility of RF ablation, RF lesions were created repeatedly at the identical anatomic site in the right atrium (n=8 swine). Average distance of the repeated right atrial ablations was 3.92±0.5 mm. Straight 3-point lines were created in the right and left ventricles to determine the ability to facilitate complex ablation procedures (n=6 swine). The ventricular lesions deviated 1.70±0.24 mm from a straight line, and the point distance differed by 2.25±0.63 mm from the pathological specimen.

Conclusions—Real-time display of the catheter position on 3D MRI allows accurate and precise RF ablation guided by the true anatomy. This may facilitate anatomically based ablation procedures in, for instance, atrial fibrillation or nonidiopathic ventricular tachycardia and decrease radiation times. (Circulation. 2003;108:2407-2413.)

Key Words: catheter ablation imaging electrophysiology arrhythmia

Catheter ablation has become first-line therapy for many cardiac arrhythmias, including atrioventricular nodal reentrant tachycardia, atrial flutter, and accessory pathway-mediated arrhythmias. Attempts to ablate more complex arrhythmias, such as atrial fibrillation and nonidiopathic ventricular tachycardia, have proved more challenging.1,2 Ablation strategies based on anatomic considerations rather than mapping may improve the efficacy of the catheter ablation for these more complex arrhythmias. Anatomic knowledge of the pulmonary veins and the atrio-pulmonary junction has become a critical part of pulmonary vein ablation for paroxysmal atrial fibrillation.2-4

However, fluoroscopy can supply only limited information about the 3D cardiac morphology and allows only an incomplete assessment of myocardial soft-tissue structures.3-4 Fluoroscopy times >1 hour are not uncommon for these complex procedures and expose the patient and the staff to significant ionizing radiation.5

Therefore, 3D electroanatomic mapping systems have played an increasingly important role in facilitating catheter ablation procedures in the setting of complex arrhythmia substrates.3-6,7 These systems allow the catheter tip to be displayed within an electroanatomic map of the heart. However, these mathematically reconstructed maps are simplified and lack detailed anatomic information.7

The purpose of this study was to create a true anatomically based catheter-guiding system by superimposing electromagnetic catheter tip tracking technology on 3D MR images. In a multiple-step approach, we evaluated this positioning system for (1) its in vitro accuracy and precision in a phantom model, (2) its in vivo accuracy and precision during catheter navigation in an animal study, (3) its reproducibility for radiofrequency ablation (RFA) in the right atrium, and (4) its position error when guiding the creation of linear lesions (ventricular 3-point line).

Methods

Phantom and Animal Preparation

A 20×20×20-cm Plexiglas cube was used for the phantom study. Before MR imaging, 12 self-adhesive skin markers (fiducial mark-
Figure 1. Experimental setup. Triangular location pad is placed under animal in fluoroscopy suite (black arrow). Registration is performed using fiducial surface markers applied to animal’s chest (white arrow). Reference catheter (asterisk) is taped to animal’s chest.

**MR Imaging**

The phantom or animal was imaged in a 1.5-T closed-bore MRI system (Signa LX, GE) using a cardiac phased-array coil. Continuous axial images were acquired using a 3D fast gradient echo recall sequence (TE, 5 ms; TI, 200 ms; flip angle, 25°; readout bandwidth, 32 kHz; 256×160 matrix; field of view, 25 cm; slice thickness, 1.8 mm with 0.9-mm reconstruction; inverse recovery).

For the animal studies, the MRI was acquired ECG-triggered from the 3D MR images in real time. A reference catheter on the chest of the animals helped to maintain the image registration during respiratory or positional changes.

**Image Registration**

Each fiducial skin marker on the object was touched with the tip of the ablation catheter. At the same time, the corresponding marker on the computer image was identified by a mouse-driven cursor, resulting in a point-pair file. Software supported construction of a transformation matrix allowed for the registration process, superimposing the 3D MRI and the live animal or phantom.

**Assessment of In Vitro Accuracy and Precision in the Phantom Study**

To test the precision, a virtual point was calculated, which represented the average of the 7 independent measurements per marker in 3D space. The distance from each of the 7 recorded points to this virtual point was measured. The precision was assessed individually for each of the 12 surface markers.

**Assessment of In Vivo Accuracy and Precision in the Animal Study**

The 8F ablation catheter was inserted through the arteriovenous sheath and advanced to the right or left ventricle. Real-time movement of the catheter was observed as a crosshair displayed on the MR images. Correlation with biplane fluoroscopic images was observed after the catheter was positioned in the right atrium, atrial appendage, and right or left ventricle.

After the catheter was withdrawn, 7 repeated recordings at each of the 9 to 12 external surface markers were performed to determine the accuracy and precision as described above (n = 7 swine).

**Assessment of Reproducibility for RFA**

The aim of this experiment was to perform 3 individual point ablations at a single anatomic site (n = 8 swine). After selection of a target site on the MRI at the lateral right atrial wall, the 8F ablation catheter was directed 3 times to this site, and an RFA was performed with a power-controlled mode at 30 W for 45 seconds with an impedance <150 Ω (Attakor, Medtronic). After each ablation, the catheter was pulled back into the venous sheath. At the end of the experiment, the heart was excised. The distance between the centers of the ablation site and the total area of the combined lesion were measured. Results were confirmed after histological staining with Masson’s trichrome and hematoxylin-eosin.

**Assessment of Position Error During Creation of a Ventricular 3-Point Lesion**

The purpose of this study was to place 3 RFA lesions in a straight line in the right or left ventricle (n = 6 swine). With an 8F ablation catheter, 3 ablation sites along a straight line were selected on the MR scan, and RFA was performed with a power-controlled mode at 30 W for 60 seconds at each of the sites while the impedance was monitored. After the experiment, the animal was euthanized. To evaluate the precision to create a straight line, the shortest distance from the middle lesion to a line connecting the 2 outward lesions was determined on the gross specimen (see Figure 4B). In addition, the total length of the ablation line was measured on the

**Navigation System**

The navigation system (Magellan, Biosense Webster) can display the catheter position on 3D data sets like 3D MRI in real time. After returning to the fluoroscopy suite, the location pad was placed under the phantom or swine (Figure 1). It contains 3 electromagnetic coils, which generate an ultralow magnetic field (5×10^-5 to 5×10^-4 T). As these fields decay with distance, 3 orthogonal antennae in the tip of the ablation catheter (NAVI-Star, Cordis Webster) can identify its position and orientation in space (similar to a global positioning system) and display its location on the 3D MR images in real time. A reference catheter on the chest of the animals helped to maintain the image registration during respiratory or positional changes.
tissue sample and compared with the distances recorded by the navigation system. Ablation sites were confirmed after histological staining.

Statistics
Results are reported as mean±SEM. Correlation coefficients were calculated with the Pearson test. A value of $P<0.05$ was considered statistically significant.

Results

Assessment of In Vitro Accuracy and Precision in the Phantom Study
The average distance from the indicated to the actual position (accuracy) was $1.11±0.06$ mm. The average distance from the indicated position to the geometric mean of all measured positions (precision) was $0.30±0.07$ mm.

Assessment of In Vivo Accuracy and Precision in the Animal Study
Figure 2 shows a representative image during navigation through the left ventricle. The catheter position is updated in real time and is displayed as a yellow crosshair at the medial aspect of the anterolateral papillary muscle. The detailed cardiac anatomy with mitral valve, left atrium, and a common ostium of the right superior and inferior pulmonary veins are easily visible on the MR image.

Catheter navigation was performed successfully through the great vessels to the right atrium, the right ventricle, and the left ventricle in 7 swine. During the catheter manipulation, the crosshair was displayed continuously on the intravascular lumen, which served as an estimate of good registration quality. Fluoroscopy was used only after the catheter had been placed in the right atrium, right ventricle, and left ventricle and showed an excellent correlation.

Accuracy and precision were calculated from 7 independent location recordings per individual surface marker in each of the 7 animals and were $2.74±0.52$ and $1.97±0.44$ mm, respectively. The position error was significantly higher in the animal experiments than the phantom study ($P<0.01$ for accuracy and precision, respectively).

Assessment of Reproducibility for RFA
Figure 3A shows a representative experiment, which demonstrates the typical monitor display during the last of the 3 ablations at the lateral right atrial wall. The catheter position (yellow crosshair) and the 3 ablation sites are shown on coronal, sagittal, and axial MR images and in a 3D reconstruction of the heart. No fluoroscopy was used during the experiments. After the animal had been killed, the distance between the centers of the individual ablations were measured on the corresponding tissue specimen (Figure 3B) and are reported in Table 1 for all 8 swine. The average distance between the centers of the 3 ablation points was $3.92±0.50$ mm.

Assessment of Position Error During Creation of a Ventricular 3-Point Lesion
Figure 4A shows a typical experiment. The catheter position (yellow crosshair) and the ventricular ablation sites (black markers/white arrows) are seen along the left ventricular septum in coronal, sagittal, and axial images and in a transparent 3D model. Experiments were performed without fluoroscopy.

On the corresponding pathological specimen, the shortest distance from the middle lesion to a line connecting the 2 distal lesions was recorded (Figure 4B) and is shown for each of the 6 individual experiments in Table 2. The average position error was $1.70±0.24$ mm. In a second assessment, the total length of the 3-point line in the tissue specimen was compared with the recorded length of the navigation system. The average difference was $2.25±0.63$ mm (correlation coefficient $r=0.93$; $P<0.05$).

Discussion

Main Findings
The results of this study demonstrate that the concept of stereotactic catheter guidance can be applied to the field of cardiology and allows anatomically guided RFA. Our findings indicate that (1) 3D MR images of the chest can be successfully combined with a low magnetic field catheter sensing method to yield an anatomically based real-time positioning system, (2) intravascular and intracardiac navigation can be performed reliably without fluoroscopic guidance, and (3) true anatomically guided placement of RFA lesions is reproducible and accurate.

Anatomic Guidance
Since the 1950s, stereotactic systems have allowed true anatomical catheter guidance combining MR or CT images in neurosurgery, otorhinolaryngology, and oncology. In electrophysiology, other technologies, such as intracardiac endoscopy and echocardiography, were used for morphological catheter navigation. More recently, new technologies using anatomically approximated reconstructions became available for electroanatomical catheter guidance.

The CARTO system (Biosense Webster) reconstructs cardiac chambers from multiple catheter recordings along the
A limitation of these currently available imaging systems is that they rely on mathematically reconstructed cardiac chambers and cannot accurately describe true 3D morphology. A, Right atrial ablation. MR images are displayed in coronal, sagittal, and axial views. Catheter tip is displayed as a yellow crosshair and moves in real time as catheter is manipulated. Three labels (yellow-black) indicating 3 independent ablation sites are seen at center of crosshair in all 3 imaging planes. Right lower quadrant displays 3D reconstruction of heart and great vessels. Catheter position is indicated by gray 3D axis. B, Right atrial ablation. Gross pathology of 3 ablation lesions (white arrows) created on lateral wall of right atrium as shown in A.

Stereotactic Guidance During Catheter Ablation

In this study, we guided catheter navigation with the anatomic information from a previously acquired MRI.

The results of this study reveal that using external and internal markers, the position error of anatomically guided catheter navigation and RFA ranged from 2.0 to 2.7 mm and from 1.7 to 3.9 mm, respectively. Both methods have been validated in various studies. Our results confirm and extend previous studies with an identical system using MRI- or CT-guided stereotactic catheter.
guidance for neurosurgical procedures in animals and humans, transhepatic portosystemic shunt placement in swine, and a clinical bronchoscopy study. Position error in these reports ranged between 2.8, 3, and 5.6 mm, respectively.

MRI has a high soft-tissue resolution, which makes it the preferred imaging modality to accurately image even complex anatomy, e.g., in congenital heart disease or cardiomyopathy. MR scans were acquired as a 3D volume, which significantly decreased the scan time to ~90 seconds and increased the signal-to-noise ratio. The selected slice thickness of 1.8 mm (overlap reconstruction to 0.9 mm) allowed a resolution in the millimeter range, which provided sufficient anatomic detail while achieving short scanning time. The resolution could be increased further in areas of interest like the cavotricuspid isthmus or the posterior left atrial wall.

Figure 4. A, Ventricular 3-point ablation line. Catheter position is displayed as yellow crosshair on MR images in coronal, sagittal, and axial views and updated in real time. Three ablation sites along left ventricular septum are marked with yellow-black labels (white arrows). One of 3 ablation lesions is out of current imaging plane in coronal views. Transparent 3D reconstruction in right lower quadrant allows visualization of ventricular ablation lesions (white arrows). B, Ventricular 3-point ablation line. Gross pathology of 3-point ablation line (white arrows) along left ventricular septum as shown in A. To assess position error, distance of middle lesion from a line connecting 2 distal lesions (dotted line) was measured and total length of 3-point line in specimen and navigation system compared.
The catheter navigation was performed by use of the axial, coronal, and sagittal display of the original MR dataset. However, the contrast enhancement with gadolinium allowed 3D reconstruction with an integrated software program for edge detection with additional manual editing tools for low-contrast areas. The electromagnetic catheter location unit itself, which is also used in the CARTO and the NOGA systems, has been shown by Gepstein et al.\textsuperscript{12} to be very accurate and precise, with a position error $H1_{1021} 1 \text{mm}$. This investigational guiding system acquires the catheter position up to 30 times per second. Along with the cardiac and respiratory cycles, this resulted in a cyclic motion of the catheter tip of several millimeters. To place a point tag or an ablation, the catheter was manipulated until the center of the displayed cyclic catheter positions during several cardiac and respiratory cycles was over the selected target site. Point tags were then acquired during end expiration, and location (and distances) were calculated by the electromagnetic positioning system alone.

Our position errors during RFAs ranged from $1.70 \pm 0.24$ to $3.92 \pm 0.50 \text{ mm}$, which is less than the size of the ablation catheter tip electrode and an average ablation lesion. This confirms the results of the currently available mapping systems, which were in a similar range. Shpun et al.\textsuperscript{11} reported a position error of $2.3 \pm 0.5 \text{ mm}$ during ventricular ablations using the CARTO system. Gornick et al.\textsuperscript{19} measured an accuracy of $4 \pm 3.2 \text{ mm}$ with the Ensite system, and Wittkampf et al.\textsuperscript{14} and de Groot et al.\textsuperscript{6} achieved an position error of $\approx 2 \text{ mm}$ with the LocaLisa and the Cardiac Pathways system.

### Current Limitations of Stereotactic RFA

The investigational system used in this study has several limitations. While arrhythmias like atrial fibrillation can hamper the quality of MRI, aggressive heart rate control and careful protocol selection can frequently achieve acceptable results. Alternatively, this guiding system can also use contrast-enhanced CT images (less susceptible to arrhythmias) until newer gating technologies become widely available.

The previously acquired 3D MR images cannot visualize interval changes in the heart size because of differences in rate or contractility. Furthermore, a static dataset is limited in its correction for the cardiac and respiratory motion as well as body movements during the procedure. However, the concept

<table>
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<th>Experiment</th>
<th>Area Shape</th>
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<th>Area, mm$^2$</th>
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<th>AC</th>
<th>BC</th>
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Mean ... ... 47.3 3.92 ... ...
SEM ... ... 12.9 0.5 ... ...
Minimum ... ... 19.6 0 ... ...
Maximum ... ... 132.0 9 ... ...

Lesion size and shape are shown for each resulting ablation lesion as determined by pathology. Distances between each of the 3 individual lesions are listed as AB, AC, and BC.

### TABLE 2. Ventricular 3-Point Ablation Line

<table>
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<tr>
<th>Experiment</th>
<th>Distance, mm (Middle Lesion)</th>
<th>Line Length, mm (Pathology)</th>
<th>Line Length, mm (Navigation System)</th>
<th>PE, mm</th>
<th>PE, mm (Absolute)</th>
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<td>1.15</td>
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</table>

PE indicates position error. Deviation of an ideal straight line is measured as the distance of the middle lesion from a line connecting the 2 distal ablations. Comparison of actual line length, its length indicated with the navigation system, and the PE is indicated for each single experiment.
of a static display without a dynamic “beating heart” has been successfully validated in other electroanatomic mapping systems, eg, the CARTO system (Biosense-Webster) and has been sufficiently accurate for a variety of different ablation procedures, especially in the atria.3,7,11,12 In addition, MRI cine loops acquired at different time points of the cardiac cycle could be displayed with ECG linkage as a beating heart and further decrease the position error.

The non–ECG-triggered display and the acquisition rate of up to 30 times per second may be helpful in determining the ablation site compared with a single display per cardiac cycle as, eg, in the CARTO system. Electrophysiologists are familiar with catheter tip motions during the cardiac cycle from fluoroscopy, where it provides additional feedback of wall contact and location.

Respiratory motion was minimized by linking RFA and placement of point tags to the end-expiratory phase. A reference catheter on the animal’s sternum helped to correct further for respiratory motion. Body movements were minimized by anesthesia and, as in the CARTO system, partially accounted for by the reference catheter. The periods between MR scanning and RFA were kept to <4 hours to limit interval changes.

Placement of the reference catheter in the coronary sinus to account more accurately for respiratory or cardiac motion and an alternative form of registration using intrathoracic structures are possibilities to further enhance accuracy and precision.15

Clinical Implications

The importance of an anatomically based approach for many catheter ablations has been well recognized. Ablation of the tricuspid isthmus in typical flutter is purely anatomically based and so successful that it is now considered first-line therapy.20 In paroxysmal atrial fibrillation, a purely anatomic approach with circumferential isolation of the pulmonary veins has been reported to be most successful.3,7 Catheter-based strategies to simulate the surgical Maze procedure are also anatomically based and can be highly successful in the treatment of atrial fibrillation.21

This novel system uses MRI-based stereotactic catheter guidance, which displays the true cardiac anatomy in relation to the ablation catheter. This detailed anatomic information cannot be obtained either with fluoroscopy or with any of the other currently available mapping systems.

Additional projects could superimpose the electrical mapping capabilities of the CARTO system on the MR images, resulting in a true electroanatomic mapping system. Future studies are needed to investigate whether these advantages of real-time anatomic guidance translate into improved procedural success and decreased radiation exposure.

Acknowledgment

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References

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