Mapping of Atrial Activation With a Noncontact, Multielectrode Catheter in Dogs

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Background—Endocardial mapping of sustained arrhythmias has traditionally been performed with a roving diagnostic catheter. Although this approach is adequate for many tachyarrhythmias, it has limitations. The purpose of this study was to evaluate a novel noncontact mapping system for assessing atrial tachyarrhythmias.

Methods and Results—The mapping system consists of a 9F multielectrode-array balloon catheter that has 64 active electrodes and ring electrodes for emitting a locator signal. The locator signal was used to construct a 3-dimensional right atrial map; it was independently validated and was highly accurate. Virtual electrograms were calculated at 3360 endocardial sites in the right atrium. We evaluated right atrial activation by positioning the balloon catheter in the mid right atrium via a femoral venous approach. Experiments were performed on 12 normal mongrel dogs. The mean correlation coefficient between contact and virtual electrograms was 0.80 ± 0.12 during sinus rhythm. Fifty episodes of atrial flutter induced in 11 animals were evaluated. In the majority of experiments, complete or almost complete reentrant circuits could be identified within the right atrium. Mean correlation coefficient between virtual and contact electrograms was 0.85 ± 0.17 in atrial flutter. One hundred fifty-six episodes of pacing-induced atrial fibrillation were evaluated in 11 animals. Several distinct patterns of right atrial activation were seen, including single-activation wave fronts and multiple simultaneous-activation wave fronts. Mean correlation coefficient between virtual and contact electrograms during atrial fibrillation was 0.81 ± 0.18. The accuracy of electrogram reconstruction was lower at sites >4.0 cm from the balloon center and at sites with a high spatial complexity of electrical activation.

Conclusions—This novel noncontact mapping system can evaluate conduction patterns during sinus rhythm, demonstrate reentry during atrial flutter, and describe right atrial activation during atrial fibrillation. The accuracy of electrogram reconstruction was good at sites <4.0 cm from the balloon center, and thus the system has the ability to perform high-resolution multisite mapping of atrial tachyarrhythmias in vivo. (Circulation. 1999;99:1906-1913.)

Key Words: atrial flutter ■ fibrillation ■ mapping

Multisite cardiac activation mapping with roving diagnostic catheters has provided insight into the mechanism and origin of a number of clinical and experimental arrhythmias.1–3 Although intraoperative, computerized, multisite mapping techniques have proved useful during arrhythmia surgery, endocardial catheter mapping is limited by the number of simultaneous-acquisition sites that are available at a single time point.4 Approaches to multisite endocardial mapping include standard multielectrode catheters, expanding electrode arrays,1 or mobile magnetic localizing catheters.3 One other potential approach is to use a mathematical inverse solution to “estimate” electrical potentials at sites that are not in direct contact with an electrode catheter.6–9 The purpose of the present study was to determine the feasibility of a novel multisite, noncontact electrode catheter in mapping atrial activation.

Methods

Data-Acquisition System Overview

The data-acquisition system consists of a 9F catheter with a multielectrode array (MEA) mounted on a balloon and a data-analysis workstation.6,16 The electrode array is used to record intracavitary potentials that are “projected” to the endocardial surface by the workstation by use of a boundary-element inverse solution. The system also has the capability to localize a roving catheter in 3-dimensional space within a computerized reconstruction of the cardiac chamber.

Catheter

The 9F multielectrode catheter consists of 64 electrodes deployed on an inflatable ellipsoidal 7.5-mL balloon. The inflated dimension...
sions are 1.8×4.6 cm. Once positioned in the cardiac chamber, the balloon is deployed by injection of a 50-50 mixture of contrast media and saline. The recording portion of the catheter is shown in Figure 1.

**Data-Analysis System**

The computerized data-acquisition system (Endocardial Solutions, St. Paul, Minn) is based on a Silicon Graphics Indigo workstation. It has 100 analog inputs consisting of 64 inputs from the MEA catheter, 12 surface ECGs and 16 unipolar or bipolar catheter inputs, and 8 user-defined analog-signal inputs. The analog inputs are A to D converted at 1200 Hz and filtered at 0.1 to 300 Hz. After data acquisition, reconstructed electrograms were examined while being accessed from disk storage in a playback mode. The system is able to compute all 3360 local electrograms in 10% of real time in the playback mode.

Right atrial geometry was estimated by use of a contoured-geometry approach (Figure 2). In this approach, a standard electrophysiological catheter through which a locator signal is emitted is moved rapidly to trace the endocardial surface of the right atrium. Once the collection of locator points is complete, the contoured-geometry method uses a convex-hull algorithm. This effectively ignores points interior to the facets created by the convex hull. The entire data-acquisition process for right atrial geometry was performed in <3 minutes. Anatomic reference points were obtained by user-defined labeling of fluoroscopic catheter positions.

**Electrical Activity**

The potential distribution on the surface of the MEA electrodes is dependent on the underlying endocardial potentials and on the distance between the endocardial surface and the MEA electrodes. A boundary-element inverse solution based on Green’s second formula was used in the present study. Electrical data are displayed in several ways. Dynamic isopotential maps constructed from the multiple electrograms are available for display. Digital bipolar electrograms can be computed from the unipolar electrograms.

**Experimental Protocol**

Experiments were performed on 12 normal mongrel dogs. The animals were anesthetized with sodium pentobarbital and ventilated with 1% to 2% isoflurane delivered in oxygen. The animal care committee at the Minneapolis VA Medical Center approved the protocol. Standard electrical catheters with a 2.5-mm interelectrode distance were introduced via the femoral vein and placed within the right atrium and the coronary sinus. The MEA mapping catheter was introduced by the contralateral femoral vein. In the first 9 experiments, 3 quadripolar catheters were placed in the right atrium. Repeated episodes of atrial flutter and fibrillation were induced, and correlations between virtual and contact recordings were performed at 2 to 8 sites within each arrhythmia episode. In the second set of experiments, 2 decapolar catheters were placed within the right atrium to allow 20 simultaneous electrograms to be recorded. All 20 electrode recordings were used for correlations.

In both groups of experiments, recordings were performed during sinus rhythm, atrial pacing, and induced atrial flutter and fibrillation. To validate the accuracy of electrogram reconstruction from the MEA catheter, a roving catheter was moved from 6 to 10 sites throughout the atrium, including several sites in the mid right atrium. Atrial flutter and fibrillation were induced by decremental high-current right atrial pacing. Atrial tachyarrhythmias that were evaluated lasted from 5 seconds to >5
minutes. Arrhythmias terminated spontaneously or were terminated by direct current cardioversion (n=2 experiments). From 10 seconds to 2 minutes of data were acquired during each arrhythmia episode.

**Geometry Validation**

To validate the accuracy of the locator signal and the 3-dimensional contoured-geometry representation, the locator signal was used to estimate distances between electrodes on a multipolar catheter. A multipolar catheter consisting of ring electrodes separated by ~5.5 mm was positioned at 10 different sites within the right atrium in each of 3 experiments. We determined the accuracy of locator measurements by comparing the interpolar distance measured by an optical micrometer with the interpolar distance determined by the locator signal by use of 3-dimensional calculations.

**Data Analysis**

To validate the accuracy of virtual electrograms, a template-matching algorithm was used. Analysis was performed on randomly selected 2-second windows. The algorithm was used to determine a cross-correlation coefficient indicating the similarity between 2 signals, in this case represented by a contact unipolar electrogram from a standard electrophysiology catheter and a virtual electrogram computed by the data-acquisition system. The result is a spectrum of correlations indexed by the timing offset (in samples) between the 2 electrograms. The point of the maximum correlation determines the timing error (Figure 3). During sinus rhythm and atrial flutter, the algorithm was used to estimate a time delay between the 2 electrograms as well as an unadjusted and adjusted (for time delay) cross-correlation coefficient. Only unadjusted correlation coefficients were used for statistical analysis. No attempt was made to assign individual “cycles” during atrial fibrillation because of the complexity of recorded electrograms. The spatial complexity of local electrical activation was determined by evaluation of the correlation coefficient between contact unipolar electrograms recorded from sites 2.5 mm apart. Sites with high correlation coefficients were defined as having a high degree of organization or low complexity. Evaluation of the accuracy of electrogram reconstruction at specific locations within the right atrium or at particular distances from the MEA catheter was performed by linear regression. Reentrant circuits were defined by activation spanning the entire tachycardia cycle length. If >75% of the cycle length but <100% (±10 ms) was identified, an incomplete reentrant circuit was said to be present. Data are expressed as mean±SD. A P value of <0.05 was taken as significant. Cross-correlation coefficients were expressed by R values, whereas $R^2$ values were used to define linear regression comparisons.

**Results**

**Validation of Locator Signals and Geometric Measurements**

A total of 210 interelectrode distances were evaluated. The mean difference between the measured and computed inter-electrode distance was 0.09±1.3 mm. The mean absolute value of the difference between computed and actual inter-electrode distances was 0.96±0.77. The actual catheter distance from pole 1 to pole 8 was 38.43 mm. The same catheter was used in all experiments. The locator-signal–computed sum of segment lengths for the length of the catheter was 38.44±4.0 mm.

The distance from the balloon center and the vertical distance from the balloon equator did not affect the accuracy of distance measurements. However, only 5 and 6 sites, respectively, were >30 mm from the balloon center or balloon equator. The mean absolute error in location was 0.98±0.71 mm in sinus rhythm and 0.93±0.46 mm in atrial fibrillation. This difference did not approach significance.

**Sinus Rhythm**

Activation patterns during sinus rhythm demonstrated uniform impulse spread from a point in the superolateral right atrium to the remainder of the chamber. The mean correlation coefficient at all sites between virtual and contact electrograms was 0.80±0.12 at 119 sites evaluated during sinus rhythm. An example of a corresponding contact and virtual electrogram during sinus rhythm is shown in Figure 4 (top). The mean difference in activation times between the virtual and contact electrograms was 1±4 ms. A snapshot of an isopotential map obtained in sinus rhythm near the end of right atrial activation is shown in Figure 2. In 11 of 12 experiments, the region of latest activation within the right atrium was located in the midseptum. Activation in this region proceeded caudocranially toward the His bundle. Virtual unipolar and bipolar
electrograms recorded from this region showed discrete potentials similar to those described as A-Sp potential followed by “slow waves” (Figure 4, bottom). Sites at which either only slow waves or only rapid deflections between the A and V electrograms appeared were also seen.

**Atrial Flutter**

Episodes of atrial flutter were induced in 11 animals. In 8 of these animals, complete or incomplete circuits within the right atrium were noted. A total of 50 recordings were analyzed. The mean atrial flutter cycle length was 138±12 ms. An isochronal activation map generated from noncontact electrograms during an episode of induced atrial flutter is shown in Figure 5. At 16 sites identified on the map, unipolar contact electrograms were recorded. An example of the correlation between contact and virtual electrograms at 1 of these sites is shown in Figure 6 (top). Figure 6 (bottom) also shows several virtual electrograms obtained from the map in Figure 5. The mean correlation coefficient between contact and virtual electrograms during all episodes of atrial flutter was 0.85±0.17. The mean difference in activation times between contact and virtual electrograms was 2±4 ms.

**Atrial Fibrillation**

Episodes of atrial fibrillation were induced in 11 animals. The mean cycle length of atrial fibrillation was 130±12 ms. In some experiments, multiple simultaneous wave fronts were seen in the right atrium. In others, a single activation wave front was present at 1 time. A snapshot from an isopotential map within the right atrium and the match between virtual and contact electrograms are shown in Figure 7. Correlation between virtual and contact electrograms was evaluated at 156 sites. The mean correlation coefficient between virtual and contact electrograms was 0.81±0.18 during atrial fibrillation.

**Factors Affecting the Accuracy of Electrogram Reconstruction**

There was no significant difference in the accuracy of electrogram reconstruction among data recorded in sinus rhythm, atrial flutter, and atrial fibrillation. However, at a distance >40 mm from the balloon center, the accuracy of electrogram reproduction decreased (Figure 8). The mean cross-correlation coefficient was 0.82±0.16 for sites within 40 mm of the balloon center and 0.72±0.16 (P<0.05) at sites >40 mm from the balloon center. The
better electrogram reconstruction accuracy at sites close to the balloon was present regardless of the rhythm for which this relationship was evaluated. Electrogram reconstruction accuracy was good regardless of the distance between the site of interest and the balloon equator (Figure 9).

The spatial complexity of electrical activation was determined by analysis of cross-correlation coefficients between contact electrograms recorded from electrodes with a 2.5 mm center-to-center interelectrode distance. Sites with low cross-correlation coefficients between adjacent contact electrograms showed much poorer electrogram reproduction by the noncontact mapping method than did other sites. This relationship is shown in Figure 10. When only sites with low spatial complexity of electrical activation were included (cross-correlation coefficient of adjacent contact electrograms >0.70), the accuracy of electrogram reproduction was excellent (mean correlation coefficient 0.84±0.13). In contrast, when only sites with high spatial complexity were included, the accuracy of electrogram reproduction was not as high (mean cross-correlation coefficient 0.60±0.23; P<0.001 versus low-complexity sites). To assess the spatial resolution of the inverse solution in areas of high electrical complexity, virtual electrograms at adjacent sites were also examined by creation of a color map of cross-correlation coefficients throughout the atrial endocardium. The highest cross-correlation coefficients between contact and virtual electrograms were found at computed sites within 2 to 3 mm of the contact electrograms.

Discussion

The major finding of the study is that right atrial activation in this model can be accurately reproduced with a noncontact electrode catheter. The catheter is capable of reconstructing electrograms and evaluating activation through-
out most of the canine right atrium on a single cycle and appears to have the ability to map rhythms such as atrial fibrillation in which beat-to-beat activity may not be constant. Finally, endocardial activation patterns in this model showing right atrial reentrant activation during atrial flutter and a variety of atrial activation patterns during atrial fibrillation correspond qualitatively to prior studies using single-point endocardial mapping and to multisite epicardial activation patterns.

Noncontact Electrode Mapping
Evaluation of distant endocardial potentials from an intracavitary electrode represents a specialized case of solution to the “inverse problem.”9,15 The present report describes the validation of a clinically applicable in vivo system for evaluation of endocardial potentials and activation patterns from intracavitary recordings in the right atrium. The accuracy of electrogram reconstruction was similar to that previously reported in the human left ventricle16 but not as good as that seen in the dog left ventricle under carefully controlled conditions.17 Although the overall system performance was good, some limitations were noted. Accurate electrogram reconstruction was obtained only at sites within 4.0 cm of the balloon center. This could limit the clinical applicability of the system in patients with large cardiac chambers, or it could require balloon repositioning to areas of interest. Additional studies including changes in catheter design or algorithm implementation will be required to determine whether this limitation can be overcome.

Geometric Modeling
The endocardial surface of the right atrium is a complex 3-dimensional structure that cannot be easily modeled by a simple 3-dimensional shape. To overcome this limitation, a contoured-geometry approach was used. This model does not detect fine details of atrial structure, such as the pectinate muscles. However, a physiologically and anatomically appropriate 3-dimensional model of the right atrium was created, as shown in Figures 2 and 5. The accuracy of the locator signal in identifying sites in 3-dimensional space was confirmed in a prior experimental study17 in which radiofrequency lesions were delivered to pacing sites at which localization was provided by the locator signal. In the present study, the locator signal was accurate to within 10% (over large distances) or 1 mm (over small distances). Additional work will be required to develop an anatomic technique that provides better detail of complex 3-dimensional structures located within the heart.

Activation During Atrial Flutter and Atrial Fibrillation
Few prior studies have carefully examined pacing-induced atrial flutter in the normal canine heart.18–20 Most episodes of atrial flutter induced in the present study had characteristics that in many ways are similar to clinical atrial flutter. Atrial flutter was macroreentrant in nature, tending to proceed caudally to cranially along the septum and craniocaudally along the lateral right atrial wall. Although atrial tachycardia was not evaluated in the present study, the ability of the system to localize activation during sinus rhythm and other tachyarrhythmias suggests that it should be clinically useful in localizing atrial tachycardia.

Evaluation of activation during atrial fibrillation is a complex process, and the present study was not designed to be able to carefully evaluate reentrant activation during atrial fibrillation. However, several observations were
made that were consistent with prior experimental results. In some cases, right atrial activation was relatively uniform, although the ECG pattern was consistent with atrial fibrillation. In other cases (corresponding to what has previously been described as type III atrial fibrillation in humans), multiple simultaneous wave fronts and incomplete reentry circuits were seen in the canine right atrium.

Comparison With Other Techniques
Different techniques are available to create a representation of cardiac activation from electrical recordings. Prior studies have used either unipolar or bipolar electrograms to examine activation. The pattern of cardiac activation has been described with isochronal, isopotential, and vector mapping, in which the direction of cardiac activation is indicated by vector loops created from orthogonal bipolar electrograms. The noncontact mapping system used in the present study has the ability to create each of these representations. No “gold standard” was available to evaluate the isochronal map obtained in vivo because reconstructions even from the 16 simultaneously recorded electrodes cannot be performed with 3-dimensional accuracy. However, if activation times and electrogram morphology obtained from multiple simultaneous sites are accurate, an isochronal map generated from such data will be similarly accurate. The present study was not designed to determine the “ideal” method for cardiac mapping. It is likely that each method has strengths and limitations in individual applications.

Limitations
One implementation of a boundary-element inverse solution was evaluated in the present study. No attempt was made to compare this technique to other potential inverse-problem solutions. It is possible that other inverse solutions could provide equivalent or more accurate information. Although the mapping system has the theoretical ability to determine conduction velocity, these measurements were not available at the time the study was performed, and thus a careful examination of regions of slow conduction during arrhythmias such as atrial flutter was not possible. The present study was also not designed to evaluate the mechanism of atrial fibrillation, and only 1 model of short-term, pacing-induced atrial fibrillation was used. Thus, only a qualitative description of right atrial activation patterns is included.

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References
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