Rapid High Resolution Electroanatomical Mapping
Evaluation of a New System in a Canine Atrial Linear Lesion Model

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Background—A canine right atrial (RA) linear lesion model was used to produce a complex pattern of RA activation to evaluate a novel mapping system for rapid, high resolution (HR) electroanatomical mapping.

Methods and Results—The mapping system (Rhythmia Medical, Incorporated) uses a 6F deflectable catheter with a mini-basket (1.8 cm diameter), containing 8 splines of 8 electrodes (total 64 electrodes, 2.5 mm spacing). The system automatically acquires electrograms and location information based on electrogram stability and respiration phase. In 10 anesthetized dogs, HR-RA map was obtained by maneuvering the mini-basket catheter during sinus rhythm and coronary sinus pacing. A right thoracotomy was performed, and either 1 or 2 (to create a gap) epicardial linear lesions were created on the RA free wall (surgical incision or epicardial radiofrequency lesions). RA maps during RA pacing close to the linear lesions were obtained. A total of 73 maps were created, with 44 to 729 (median 237) beats and 833 to 12 412 (median 3589) electrograms (≤2 to ≤5 mm from surface geometry), resolution 1.8 to 5.3 (median 2.7) mm, and 2.6 to 26.3 (median 7.3) minutes mapping time. Without manual annotation, the system accurately created RA geometry and demonstrated RA activation, identifying the location of lines of block and presence or absence of a gap in all 10 dogs. Endocardial radiofrequency catheter ablation of a gap (guided by activation map) produced complete block across the gap in all 3 dogs tested.

Conclusions—The new HR mapping system accurately and quickly identifies geometry and complex patterns of activation in the canine RA, with little or no manual annotation of activation time. (Circ Arrhythm Electrophysiol. 2012;5:417-424.)

Key Words: electrophysiology mapping • catheter ablation • radiofrequency • tachyarrhythmias

Current 3-dimensional electroanatomical mapping systems accurately localize the site of earliest activation in focal tachycardias, identify the reentrant circuit, and localize arrhythmogenic channels in macroreentrant tachycardias.1–3 However, current electroanatomical mapping systems are limited by (1) point-by-point mapping data acquisition, (2) requiring a large number of mapping sites for high resolution (3–4 mm in areas of interest), and (3) the need to individually annotate the activation time at sites with complex electrograms (low amplitude potentials, double potentials, or fractionated electrograms) in scarred myocardium.2–7 Noncontact mapping systems have difficulty reconstructing low amplitude potentials (scarred regions), and mapping accuracy is limited to sites close to the probe.8–11

Clinical Perspective on p 424

A new mapping system using a small basket array of 64 electrodes has been developed to rapidly obtain a high resolution electroanatomical activation map with little or no requirement for annotation (ie, automatic). The purpose of this study was to evaluate the resolution and accuracy of this novel mapping system using a canine model with lines of conduction block in the right atrium created by ablation or surgery. We tested the ability of the system to localize the lines of block and identify the presence or absence of gaps in the lines of block.

Methods

Mapping System

The mapping (minibasket) catheter has an 8F bidirectional deflectable shaft and a basket electrode array (normal mapping diameter 18 mm) with 8 splines, each spline containing 8 small (0.4 mm2), low impedance electrodes (total 64 electrodes, Rhythmia Medical, Incorporated; Figure 1). The interelectrode spacing along the spline is 2.5 mm (center-to-center). Mapping can be performed with the basket in variable degrees of deployment (diameter ranging 3–22 mm). The location of each of the 64 electrodes is identified by a combination of a magnetic sensor in the distal region of the catheter and impedance sensing on each of the 64 basket electrodes. The location of each basket electrode is obtained whether the basket is fully or only partially deployed. Heparinized saline (1 U/mL) was infused through the central lumen of the catheter shaft at 1 mL/min, emerging at the proximal end of the basket to prevent thrombus.

Cardiac beats were selected for inclusion in the map based on 4 criteria, (1) cycle length stability, (2) relative timing of reference electrograms, (3) electrode location stability, and (4) respiratory gating. The criteria are selected by the operator before beginning the map. In the first 2 dogs, beats meeting these criteria were selected manually. In dogs 3 and 4, beats were selected manually in some
maps and were selected automatically (based on the above criteria) in other maps. In the last 6 dogs (5–10), beats were selected automatically for inclusion in all maps (Table).

For activation time, the system combined unipolar and bipolar electrograms to reduce far field components. Electrogram timing was based on the maximum negative dV/dt of the unipolar electrogram or maximum amplitude on the bipolar electrogram. For electrograms with multiple potentials, the system considered the timing of the potentials found with the available algorithm to select the potential to use for timing annotation. Because of the low noise level (usually <0.01 mV) due to the use of a low noise amplifier and 60 Hz noise rejection, scar (no potential) was defined as peak-to-peak bipolar and unipolar amplitude <0.03 mV.

The chamber surface geometry was generated using the location of the outermost electrodes, gated to the respiratory and cardiac cycles, and was updated continuously. The mapping system was able to select, as “surface electrograms,” all electrograms recorded within a specific selected distance of 1 to 5 mm from the surface geometry. In the first 6 dogs, activation maps were created using electrograms within 5 mm of the surface reconstruction. In dogs 5 and 6, maps were obtained using electrograms located within 3, 3.5, 4, or 5 mm of the surface. In dogs 7–10, activation maps used electrograms located only within 2 mm or 3 mm of the surface.

Activation and voltage maps were initially examined without changing the timing annotation selected by the system. The activation sequence in selected areas was reviewed rapidly by sliding a probe over the map display. As the probe is moved, the electrogram recorded closest to the location of the probe was displayed, allowing manual reannotation of activation time if not correct.

The resolution for each map was estimated by dividing the average edge length of 0.6 mm (equivalent to lead length), resulting in >40,000 vertices (Figure 2). The distance from each vertex to the nearest electrogram was averaged. The resolution of each map was described as 2 times the average vertex-electrogram distance (Figure 2D and Table).

Experimental Model

The experimental protocol was approved by the University of Oklahoma Committee on the Use and Care of Animals. Ten mongrel dogs weighing 25 to 32 kg were anesthetized with sodium pentobarbital (30 mg/kg) and ventilated mechanically with room air. The right carotid artery was cannulated for monitoring arterial pressure. The right femoral vein was cannulated using a short sheath, and advanced to the inferior vena cava (IVC) in 2 to 5 mm increments, using the mapping system display for anatomic guidance. The basket was advanced back into the right atrium and to the tricuspid annulus. The basket then was partially undeployed and advanced into the right atrial appendage. The basket was redeployed and slowly withdrawn from the appendage. The basket was finally maneuvered to sites in the right atrium that were not previously covered. The basket catheter was maneuvered easily throughout the right atrium without becoming trapped, using a variable degree of deployment when necessary. Electrode contact with the wall was monitored using the middle bipolar electrogram (electrodes 4–5) on each spline (equatorial electrograms). In the first 4 dogs, the basket was maintained at each site (usually 2–3 seconds) until the stability criteria (cycle length, reference electrograms, location, and respiratory gating) were met.
achieved, indicated by green bars on the map display, and manually accepted (Table, see Map Mode: Manual). In the remaining 6 dogs, the catheter was slowly moved and the system acquired all beats automatically using the operator defined criteria (Table, see Map Mode: Auto). The number of cardiac beats and the number of electrode sites (electrograms) acquired by the system and the time required to complete each map are listed in Table.

A right thoracotomy then was performed at the 5th intercostal space. The pericardium was opened to expose the epicardial surface of the right atrium. A linear lesion was created along the right atrial free wall using either surgical incision and suture (5 dogs) or epicardial radiofrequency (RF) applications (5 dogs). In the last 6 dogs, a gap (for conduction) was left in the linear lesion (Figure 3). Pacing electrodes were sutured to the right atrial epicardium on the anterior side of the linear lesion in the first 3 dogs, and on both anterior and posterior sides of the lesion in the remaining 7 dogs (Figure 3). The right thoracotomy was closed and the dogs were placed back into the supine position.

Following creation of the linear lesions, a map of the right atrium was obtained during right atrial pacing anterior to the linear lesion, at a cycle length slightly shorter than the sinus cycle length, in all 10 dogs. In dogs 2 and 3, a right atrial map also was obtained during sinus rhythm, with activation beginning posterior to the linear lesion. In the remaining 7 dogs (4–10), a right atrial map also was obtained during atrial pacing posterior to the linear lesion. The initial reviewer of each postlinear lesion map was blinded to the location of linear lesion and the presence or absence of a gap.

In 3 of the 6 dogs with a gap in the linear lesion, endocardial radiofrequency ablation of the gap was performed using a 4 mm tip ablation catheter guided by the location system and the activation map. Following ablation, maps of the right atrium were obtained during pacing posterior to the linear lesion in 1 dog, and pacing both anterior and posterior to the linear lesion in 2 dogs to determine whether complete conduction block across the gap was obtained, resulting in a long continuous line of block (Table).

The reproducibility of the right atrial maps was examined by repeating the map during sinus rhythm in 2 dogs, CS pacing in 4 dogs, and pacing anterior or posterior to the linear lesion in the last 8 dogs (Table). New geometry was created with each map.

At the end of the procedure, the dog was euthanized. The heart was excised for examination.

Statistical Analysis
The values are expressed as range and median or mean ± SD. For each map mode, separate maps were created and data were collected independently for each map. Nonparametric (Mann-Whitney U) tests were used to compare the projection distance for surface electrogram, mapping time, number of accepted beats, number of accepted electrograms, and mapping resolution between the Manual Map Mode and the Auto Map Mode. A probability value of <0.05 was considered to be statistically significant.

Results
Baseline Right Atrial Maps During Sinus Rhythm and Coronary Sinus Pacing
The baseline (prelinear lesion) right atrial maps obtained during sinus rhythm and CS pacing created right atrial geometry (including SVC and IVC) consistent with canine
Figure 4. Activation map during sinus rhythm of the right atrium (RA), superior vena cava (SVC), and inferior vena cava (IVC) in the right lateral (RL) and left lateral (LL) projections in dog 8 (Sinus Rhythm Map 1). Earliest activation (red) was recorded in the region of the sinus node at the SVC–RA junction. Color bar represents the range of activation time (–68 ms to 31 ms), relative to a reference electrogram in coronary sinus (CS). Sites with activation time earlier than –58 ms are displayed in red. A, Automatic map (Auto Mode) without manual annotation shows only a few small, isolated areas where the activation time was inconsistent with the timing of the surrounding area (small white arrows). The mapping system automatically accepted 463 sinus beats and 8227 “surface” electrograms recorded within 3 mm of the surface geometry. The resolution of the map was 2.3 mm. Mapping time was 8.2 minutes. B, Same map after manually annotating 10 of 8227 (0.1%) electrograms (small white arrows) to correct the activation time at several small areas.

Figure 5. Activation map during coronary sinus (CS) pacing, shown in the right lateral and left lateral projections in the same dog as figure 4 (Dog 8, CS Pacing Map 1). Earliest right atrial activation (red) was recorded at the inferomedial region of the right atrium. A, Automatic map (Auto Mode) without manual annotation shows several isolated areas where the activation time was inconsistent with the timing of the surrounding area (small white arrows). The mapping system automatically accepted 417 beats and 9298 “surface” electrograms recorded within 3 mm of the surface geometry. The resolution of the map was 2.1 mm. Mapping time was 7.9 minutes. B, Electrograms recorded during manual review using the roving probe to select individual electrograms. Tracings from the top are ECG lead V4, proximal and distal CS electrograms (CSp and CSd), bipolar (Bip 1–2) and 2 unipolar electrograms (Uni 1 and Uni 2), and the derivative of Uni 1 electrogram (U1 dV/dt) recorded from the electrode site closest to the roving probe. The mapping system incorrectly annotated the timing of His bundle activation (H, dashed red line) as local atrial activation. A, atrial potential; V, ventricular potential. C, Map after manual review, correcting activation time in 17 of 9298 (0.2%) electrograms (small white arrows), including changing the timing of His bundle activation to local atrial activation (black arrow).
cardiac anatomy by magnetic resonance imaging. The map geometry was similar within and between dogs (Figures 4 and 5). Maps during sinus rhythm demonstrated activation originating at the superior crista terminalis, consistent with the location of the sinus node (Figure 4). Maps during CS pacing showed right atrial activation beginning at the infero-medial region (Figure 5).

The automatic maps (without manual annotation) showed only a few small, isolated areas where the activation time was inconsistent with the timing of the surrounding area (small arrows in Figures 4A and 5A). Reviewing the electrograms at these sites using the roving probe on the map display confirmed that the timing annotation was not correct (Figure 5C), and allowed manual reannotation (Figures 4B and 5C, Table).

Right Atrial Maps After Creation of Linear Lesions

Right atrial maps recorded during right atrial pacing, following creation of the linear lesions, demonstrated sharply demarcated lines of conduct block, manifested by abrupt change in activation time and color in all 10 dogs (Figures 6 through 8). Electrograms along the lines of conduction block demonstrated double atrial potentials, while electrograms recorded a few millimeters on either side of the line exhibited 1 sharp (near field) potential and 1 small and rounded (far field) potential (Figure 7B).

The presence of conduction across the gap was demonstrated clearly on the activation maps and evident to the blinded reviewer in all 6 dogs with a gap (Figures 6 and 7). Bidirectional conduction across the gap was present during right atrial pacing on each side of the linear lesion in all 6 dogs (Figure 6). The separation between the double atrial potentials recorded along the linear lesion was greatest near the middle of the line and became shorter near the edges of the line (Figure 7). Electrograms recorded at the gap exhibited fusion of the 2 potentials or triple potentials (left panel in Figure 7E). Endocardial radiofrequency catheter ablation of the gap (guided by the location system and the activation map) was performed in 3 dogs. Only 2 to 3 RF applications were required to produce complete conduction block across the gap in all 3 dogs. Repeat right atrial maps after ablation of the gap demonstrated a long continuous line of block (Figure 7D and right panel in Figure 7E).

Reproducibility of Right Atrial Maps

The right atrial geometry and activation sequence were similar for maps repeated during sinus rhythm, CS pacing, and right atrial pacing after creation of the linear lesions (Figure 8).

Mapping Time and Resolution

In 16 of 73 right atrial maps, individual beats were selected when the 4 stability criteria were met (Table, see Manual Mode). These maps required 7.7 to 26.3 (median 12.45) minutes to complete and contained 44 to 105 (median 61.5) accepted beats, with 833 to 1982 (median 1528) accepted “surface” electrograms. In the remaining 57 maps, appropriate beats and electrograms were selected automatically based on the operator defined criteria (Table, see Auto Mode). These maps required only 2.6 to 14.7 (median 6.1) minutes to complete, and contained 93 to 729 (median 268) accepted beats, with 2197 to 12 412 (median 4227) accepted electrograms (Table). Compared with the Manual Mode, the Auto Mode required significantly less mapping time and included
Figure 7. Electrograms recorded close to the line of conduction block during pacing posterior to a radiofrequency (RF) linear lesion (Dog 8, Posterior Map 3), and endocardial catheter ablation of a gap between 2 linear RF lesions (Dog 8, Postgap Ablation Posterior Map 1). A, Activation map showing the location of 3 electrograms (EGM) recorded posterior (EGM Site 1), directly over (EGM Site 2), and anterior (EGM Site 3) to the sharply demarcated line of block (green-blue). The roving probe is positioned at the line of block (EGM Site 2). The silhouette of the minibasket shows the location of the electrode recording EGM Site 2. B, Low noise electrograms with double atrial potentials were recorded at all 3 sites. The electrogram at Site 1, posterior to the line, shows a large, sharp first potential (38 ms after pacing stimulus, S) and small, rounded (far field) second potential (78 ms). The electrogram at Site 2, on the line of block, shows 2 potentials of nearly equal amplitude (41 ms and 86 ms). The electrogram at Site 3, anterior to the line, shows a small, rounded (far field) first potential (35 ms) and a large, sharp second potential (78 ms). The electrograms confirm the location of line of block. C, Photograph of the epicardial surface of the right atrium shows the location of the 2 epicardial RF linear lesions (dotted blue lines) with a central gap (red arrow) and the 2 pacing sites. Left panel is an endocardial right atrial (RA) bipolar voltage map showing lower voltage (<0.1 mV, red area) along the linear RF lesions. Voltage ≤0.1 mV is shown in purple and ≥0.1 mV is shown in red. The activation map during pacing posterior to the line of block shows propagation (black arrows) around the sharply demarcated lines of block (white lines), with conduction through the gap (wiggly black arrow). The electrogram at the gap site is shown on the left panel in Figure 7E. D, Bipolar voltage and activation maps after endocardial catheter ablation of the gap using 2 RF applications (brown tags, Dog 8, Postgap Ablation Posterior Map). Bipolar voltage map shows very low voltage (<0.1 mV, red area) at the ablation sites. Activation map shows complete...
a significantly greater number of accepted beats and electrograms \((P<0.001)\).

The median resolution for the 16 maps obtained in the manual mode was 3.5 mm (range 2.9–5.3 mm). For the 57 maps obtained in the Auto Mode, the median resolution was 2.6 mm (range 1.8–4.4 mm, \(P<0.001)\).

**Requirement for Manual Annotation**

Initial blinded examination of the 73 activation maps (prior to manual annotation of activation time at any site) accurately revealed the site of earliest atrial activation, the location and extent of the lines of conduction block, and the presence or absence of conduction through a gap. Small areas of incorrect activation time were recognized easily due to the large number of surrounding sites with correct activation time (Figures 4 and 5). For the purpose of presentation, we elected to change the timing of activation (manual annotation) at 1 to 78 (median 8) sites, representing 0.01% to 2.46% (median 0.17%) of the accepted electrograms in 30 of the 73 maps (Table).

**Examination of the Hearts**

Examination of each heart following the procedure revealed no endocardial disruption, hematoma, or perforation, other than the surgical or RF lesions used to create the lines of conduction block.

**Discussion**

This new mapping system rapidly generated accurate, very high-resolution 3-dimensional activation maps in the canine right atrium. The minibasket mapping catheter with deflectable shaft and variable deployment of the basket was able to access the SVC, IVC, and entire right atrial endocardium. When the minibasket catheter was not easily advanced, the basket was partially undeployed (closed) and then advanced before redeployment. This maneuver allowed access to all sites, including the tip of the right atrial appendage, with few or no atrial extrasystoles.

The mapping system acquired a very large number of electrograms (median 4227 in Auto Mode), with a median resolution of 2.6 mm. The high resolution produced sharp demarcations in activation time, accurately localizing the lines of block and the presence or absence of a gap in the linear lesion. Endocardial radiofrequency catheter ablation of the gap (creating a continuous line of block; Figures 7D and 7E) in all 3 dogs, with only 2 to 3 RF applications, confirmed the accuracy of the activation map. The high density of data points minimized the error produced by isolated, incorrectly timed data points. It also allowed the system to select, in most instances, the correct activation time when complex multiple potentials were present by comparing the activation time at surrounding sites (Figure 7). Incorrectly annotated points were easily recognized as a small area of color, different from the color of the surrounding points (Figures 4A and 5A). These isolated, small areas were easily ignored, allowing accurate interpretation of the activation pattern in maps generated in the automatic mode. When desired, the review mode allowed the incorrect points to be quickly reannotated (Figures 4B and 5C). Although the timing annotation was rarely incorrect, the most likely reasons for the incorrect annotation points were that a low amplitude signal was marked as scar by the computer, an inconsistent beat that made it into the map, and far field or multiple components were present in the electrograms; the computer, therefore, picked the wrong one.

The small size of the electrodes and close interelectrode spacing (2.5 mm, center-to-center) produced very high resolution electrograms (Figures 4–8). Electrograms recorded

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**Figure 7 (Continued).** Conduction block across the gap, manifested as propagation around a continuous line of block (a long white line). Photograph of the RA epicardium following catheter ablation of the gap shows a continuous lesion. E. Electrogram recorded within the gap prior to endocardial catheter ablation (Pregap ablation) exhibits 4 potentials (1, 2, 3, and 4). Postgap ablation electrogram, recorded at the same site, shows diminished amplitude of potentials 1 and 2 (local activation time 50 ms after pacing stimulus) and a marked delay in potentials 3 and 4 (185 ms) with reversed order, suggesting reversal in the direction of activation (from posterior-to-anterior to anterior-to-posterior), confirming complete conduction block at the gap ablation site.
within 2 to 5 mm of the geometry surface had the high frequency characteristics of a contact electrogram. The low noise level in the system (usually <0.01 mV) allowed the recording of very low amplitude potentials, which may prove effective in reconstructing activation in scarred atrial and ventricular myocardium in patients with macroreentrant tachycardias.4,7

A major benefit of the minibasket catheter and mapping system was the rapid generation of a complete activation map. In the Auto Mode, the maps contained a median of 4227 electrograms and were completed in a median of only 6.1 minute. This novel mapping system provides the unusual combination of rapid acquisition and very high resolution.

Study Limitations
The primary limitation of this study is that mapping was performed in the relatively small canine right atrium. This canine model was chosen to create a known activation pattern to test the accuracy of the new mapping system. Further studies are required in different and larger heart chambers, and ultimately in humans. Another limitation is that the maps were not compared with maps generated by currently available mapping systems. However, accuracy of the mapping system was tested by blinding the initial reviewer to the location of the linear lesion and the presence or absence of a gap.

Conclusions
This new minibasket mapping system rapidly acquired a very large number of low noise electrograms (median resolution 2.6 mm in Auto Mode), and accurately localized the lines of conduction block, including presence or absence of a gap, in this canine right atrial model. The large number of mapping sites allows automatic selection of activation time in complex electrograms (based on the timing of surrounding electrograms), with little or no manual annotation.

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Disclosures
Drs Nakagawa and Jackman are consultants for Rhythmia Medical, Incorporated.

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