Validation of a New Noncontact Catheter System for Electroanatomic Mapping of Left Ventricular Endocardium

Charles C. Gornick, MD; Stuart W. Adler, MD; Brian Pederson, BA; John Hauck, MSEE; Jeffrey Budd, PhD; Jeff Schweitzer, MSEE

Background—Improvements in cardiac mapping are required to advance our understanding and treatment of arrhythmias. This study validated a new noncontact multielectrode array catheter and accompanying analysis system to provide electroanatomic mapping of the entire left ventricular (LV) endocardium during a single beat.

Methods and Results—A 9F 64-electrode balloon array catheter with an inflated size of 1.8×4.6 cm was used to simultaneously record electrical potentials generated by the heart and locate a standard electrophysiology (EP) catheter within the same chamber. By use of the recorded location of the EP-catheter tip, LV geometry was determined. Array potentials served as inputs to a high-order boundary-element method to produce 3360 potential points on the endocardial surface translatable into electrograms or color-coded activation maps. Three methods of validation were used: (1) driven electrodes in an in vitro tank were located; (2) waveforms generated from the array catheter were compared with catheter contact waveforms in canine LV; and (3) sites of local LV endocardial activation were located and marked with radiofrequency lesions. Tank testing located a driven electrode to within 2.33±0.44 mm. Correlation of timing and morphology of computed versus contact electrograms was 0.966. Radiofrequency lesions marked 17 endocardial pacing sites to within 4.0±3.2 mm.

Conclusions—This new system provides anatomically accurate endocardial isopotential mapping during a single cardiac cycle. The locator component enabled placement of a separate EP catheter to any site within the mapped chamber. (Circulation. 1999;99:829-835.)

Key Words: mapping • catheter ablation • arrhythmia • ventricles • electrophysiology

Improvements in catheter-based mapping of cardiac chambers are required to facilitate further advances in our understanding and treatment of arrhythmias. Current techniques using catheters with a limited number of recording electrodes guided by fluoroscopy often do not provide sufficiently rapid and accurate anatomic localization for arrhythmia characterization. Furthermore, catheter-based point mapping fails to provide a global view of chamber activation. Global activation maps may allow a better understanding of the critical elements necessary to initiate and maintain a tachycardia, thus enabling more directed therapy. Recently, noncontact electrodes/probes have demonstrated the feasibility of reconstructing endocardial activation sequences during a single cardiac cycle.1,2

This study validated the use of a noncontact, multielectrode array catheter (EnSite) and analysis system (EnSite 3000 System, Endocardial Solutions Inc) to provide electrophysiological and anatomic mapping of the entire left ventricular (LV) endocardium in a single beat. In vitro tank investigations tested system performance in an idealized environment. In vivo studies in canine LV assessed accuracy of reconstructed electrograms by comparing them with contact electrograms recorded with a standard electrophysiology catheter (EP catheter). Finally, studies in canine LV evaluated system accuracy in locating point activation sources at different endocardial sites. Guiding a standard EP catheter to this activation site uses all aspects of the system: (1) geometry setup phase, (2) reconstruction of potentials on the chamber surface, (3) marking of a site on the isopotential map, and (4) guidance of an EP catheter to the site with the locator system (EnGuide).

Methods

General Considerations

The array catheter is connected through a breakout box that also accommodates up to 32 EP-catheter electrodes (16 bipolar or unipolar recording channels) and 12-lead ECG inputs. Signals are processed in an interface unit. A computer workstation uses interface unit outputs to create electroanatomic maps and display unipolar and bipolar waveforms. A standard EP catheter is “located” by the array catheter and is used to trace the endocardial surface to reconstruct chamber geometry. Chamber geometry, known locations of array electrodes, and noncontact potentials at each electrode on the array are combined to reconstruct potentials from the endocardial surface.
Thus, a high-resolution electroanatomic map of even a single beat of either normal or abnormal rhythm can be created.

Technical Considerations

Array Catheter

The 9F array catheter has a central lumen for a 0.035-in guidewire (Figure 1). Moving distal to proximal, the catheter has a pigtail tip, ring electrode, balloon array, 2 intrachamber ring electrodes, and a fourth proximal system reference-ring electrode. The array comprises a braid of 64 polyimide-insulated, 0.003-in stainless steel wires over a 7.5-mL balloon. Electrodes at known locations were made by laser removal of 0.025 inches of insulation. When the balloon is inflated, array size is 1.8×4.6 cm.

EP-Catheter Location System

EP-catheter-tip location used a low-level, 5.68-kHz current that was sourced to the distal electrode and returned to each of 2 intrachamber ring electrodes on the array catheter. This high-frequency signal was sampled and demodulated from each of the 64 array electrodes at 100 times per second. With use of potentials from each of the array electrodes, knowledge of their position in 3 dimensions (determined by design), and knowledge of current sink-electrode positions, the location of the EP-catheter electrode within the chamber could be determined. The location method solves a point source-sink model (accounting for ambient conductivity) using a standard nonlinear least squares algorithm (Levenberg-Marquardt).

Determination of Chamber Geometry

By use of fluoroscopy and the system’s locator, a standard EP catheter is used to trace the inner surface of the chamber over a 2-minute sampling period. Sampling of the position of the catheter tip occurs with each diastole as the operator moves the catheter to locations throughout the chamber. In animals studied, average heart rate was 120 bpm, resulting in ~240 location samples. If adequate sampling was not achieved, geometry acquisition could be repeated. Sampled locations were put into a convex hull algorithm with the extrema (eliminating intracavitary points) used to build a faceted model. The latter was subjected to a smooth spline curve fit to create the chamber geometry used (contour geometry acquisition method).

Isopotential Map Generation

Array potentials were sampled at 1200 times per second and passed to a high-order boundary-element method. The boundary-element method was used in an inverse formulation to solve Laplace’s equation for each sample to yield endocardial potentials. An optimized regularization was required to produce accurate results, and a spline curve fit was used to produce 3360 potential points on the endocardial surface. Each of these potential points was represented on the chamber model by vertices of a superimposed grid. Potentials generated can be translated into electrograms, and maps can be created with colors used to represent the potentials. Maps are presented in animation to reveal activation patterns.

In Vitro Studies

Open cell polyurethane foam sections with cutouts to yield a hollow ellipsoidal chamber 7 cm across by 11 cm long were placed in a tank 30 cm high by 26 cm across (Figure 2). With the tank filled with 0.45% saline, the chamber had a conductivity of 0.7 s/m and the surrounding foam 0.25 s/m. Five electrodes were vertically placed 12 mm apart on the chamber surface, with return electrodes placed 3 cm deep in the foam.

The array catheter was fixed vertically in the chamber. Data were taken at 50, 40, 30, 20, and 10 mm from the array center horizontal to the chamber surface. Because the 5 surface electrodes were not equatorial to the array, the distance from each electrode to the array center varied from 10 to 58 mm. A custom-designed roving electrode consisted of a guidewire surrounded by a nonconducting sheath. At each of the 5 array positions, the roving electrode connected to the locator was used to obtain a representation of chamber geometry. A low-amplitude, 12-Hz sinusoidal current was applied to each of the 5 surface electrodes, creating a focal potential. Signal amplitudes measured from other surface electrodes 12 and 24 mm away were 0.25 mV and 60 μV root mean square, respectively. The center of this focal potential visible on the isopotential map was marked with available map labels.

Map labels corresponding to grid vertices were generated by the analysis system. The distance between vertices varied from 0.79 mm at 10 mm from the array center to 3.96 mm at 50 mm. There is greater distance between grid vertices as the distance from the array to the chamber surface increases, which is related to arc lengthening.

The roving electrode was directed to the labeled site with the locator and system map and anchored into the foam to mark the site. The foam wedge containing the driven and roving electrodes was removed and the distance between the electrodes measured. The wedge was reinserted and the procedure repeated with each of 5 surface electrode sites at each of 5 array positions.

In Vivo Studies

Animal studies were performed at the Minneapolis, Minn, Veterans Affairs Medical Center (accredited by the American Association for Accreditation of Laboratory Animal Care) and were approved by the institute’s Research Subcommittee for Animal Studies.

Sixteen mongrel dogs (weight, ~25 kg) were anesthetized with sodium pentobarbital (18 mg/kg IV). Animals were intubated and ventilated with a mixture of isoflurane 1% to 2% delivered in oxygen to maintain anesthesia. In 5 animals, only arterial catheterization was used to compare reconstructed endocardial electrograms with contact electrograms. In the remaining 11, succinyl choline 0.4 mg/kg was used as a muscle relaxant before thoracotomy. At the conclusion of the experiment, all animals were euthanized with sodium pentobarbitol (80 mg/kg) and sodium phenytoin (110 mg/kg).

In all 16 animals, a 9F introducer was placed percutaneously in the left femoral artery for introduction of the array catheter into the LV. An 8F introducer placed in the right femoral artery was used to introduce a 6F deflectable-tip EP catheter (4-mm-tip electrode) into the LV. In the 11 animals undergoing thoracotomy, the right external jugular vein was used for introduction of a positive fixation pacing lead to the right ventricular (RV) apex for use as a positional reference. After thoracotomy, 4 small incisions were made through the pericardium to place plunge electrodes. Plunge electrodes were constructed with 0.009-in-diameter, polyimide-insulated wire folded and inserted into a 19-gauge needle. The tips (2 mm) of the wire were stripped of insulation and folded along the shaft of the needle. The needle was advanced through the myocardium until blood flowed freely, indicating an intracavitary location. The needle was then withdrawn, leaving the electrodes hooked on the endocardial surface. A silicone plug with felt backing placed over the wires was snugly fit to the epicardial surface to hold the electrodes in place. Each electrode pair was labeled A through D in a blindered fashion such that only the technician placing them knew their location. Electrodes were placed in the anterior and anterolateral LV, with
attempts made to avoid the papillary muscles and to include sites from base to apex (Figure 3). The chest was closed, allowing no further visualization of the location of the plunge electrodes.

The array catheter was advanced into the LV with the tip in the apex. The balloon was inflated by use of a saline/x-ray contrast solution. A 6F EP catheter was advanced into the LV, connected to the system locator, and used to trace the contour of the LV. In the 5 animals in which electrogram comparisons were made, the EP-catheter tip was located within the LV chamber by use of the locator function of the system. Unipolar electrograms were recorded from the catheter tip for later comparison with computed electrograms from the same site.

In the 11 animals with plunge electrodes, LV geometry was similarly determined. The RV electrode was identified with the locator to orient septal location. Each of the 4 plunge electrodes was “located” and paced. Pacing threshold determinations (4-ms pulse width) were made at each of the electrodes. At pacing outputs just below capture level, endocardial activation was monitored to ensure the pacing stimulus artifact was not being targeted versus actual pacing-induced ventricular activation. A plunge electrode was randomly selected and paced every fourth beat with a current level 0.1 mA above threshold. This kept hemodynamic consequences at a minimum and limited the size of the pacing stimulus artifact. The analysis system was programmed to display only the paced beats. Using the generated isopotential maps and locator function, we positioned the EP-catheter tip as close to the site of onset of paced ventricular activation as possible. Using a radiofrequency (RF) generator (Radionics RFG-3B) delivering 25 W between the catheter tip and an abdominal ground pad for 2 minutes, we marked the site permanently for later autopsy evaluation. After RF lesion placement, repeat pacing threshold measurements were made. In 5 of 11 animals, a single RF lesion was placed at 1 plunge-electrode site. In the remaining 6, a single RF lesion was placed at each of 2 plunge-electrode sites. RF application frequently resulted in ventricular arrhythmias. Despite their occurrence, stability of the catheter was maintained, as confirmed by fluoroscopy and the locator function. After animals were euthanized, the array and EP catheters were removed. The RV and LV plunge-electrode positions were
preserved during cardiac removal at autopsy. The LV was opened along the posterior wall away from the location of the plunge electrodes. The site of RF lesion was documented photographically. RF lesion diameter and distance from both edge and center of lesion to the plunge electrode were measured. Careful attention was paid to the location of any trabeculations, papillary muscles, and Purkinje strands located in relation to the RF lesions or the plunge electrodes.

**Data Analysis**

In the in vitro studies, the measured distance between the roving and driven electrodes was compared by 2-way ANOVA (with array catheter and driven electrode positions serving as the 2 independent factors) with that obtained with the EnSite System.

In the in vivo studies, electrograms were computed by use of the boundary-element method at the endocardial surface location of the located EP-catheter tip, and their timing and morphology were compared with contact electrograms. Cross correlation was calculated with the equation:

\[
p = \frac{\sum_{i=0}^{n-1} (X_i - \bar{X})(Y_{i+k} - \bar{Y})}{\sqrt{\sum_{i=0}^{n-1} (X_i - \bar{X})^2 \sum_{i=0}^{n-1} (Y_{i+k} - \bar{Y})^2}}
\]

where \(X\) is the computed signal, \(Y_i\) is the contact signal, and \(k\) is evaluated over a range covering 50 to \(-50\) ms. The \(k\) at which this correlation is highest is taken as the time difference between the 2 signals. Activation timing differences are reported as mean \(\pm\) SD. In the in vivo animal studies that used location of endocardial pacing sites, the mean, median, and SD of the distance measurements were calculated.

**Results**

**In Vitro Tank Testing**

We assessed locator precision by taking the difference between positions of the driven and roving electrodes on the chamber surface as measured by the locator function. This distance was compared with the physically measured distance. Within a range of \(<50\) mm, the locator function had a precision of \(-0.33\pm0.45\) mm (negative difference indicates the locator underestimated the distance between the roving and driven electrodes). Within the range of \(<50\) mm, the roving electrode could be guided by use of the locator function to within \(2.33\pm0.44\) mm of the focal potential (driven electrode) rendered on the generated isopotential map. The position of the driven electrode on the chamber surface (ie, whether it was equatorial or polar in relation to the array) was not related (\(P=0.29\) by ANOVA) to the ability to locate it. At distances \(>50\) mm from the array to the driven electrode, the precision of the locator was reduced to \(-0.75\pm1.13\) mm. The ability to locate the focal potential by use of the isopotential map presentation was reduced to a mean of \(7.50\pm1.13\) mm (\(P<0.01\) by ANOVA).

**In Vivo Comparison of Computed and Contact Electrograms**

Timing and morphology of computed electrograms were compared with contact electrograms from the endocardial surface (Figure 4). Distances of sites from the center of the array, as measured by the locator, ranged from 9.9 to 48.1 mm (27.4\pm9.1 mm). Using correlation timing analysis (see Equation in Methods section), 567 beats were analyzed from 5 dogs (\(\approx19\) beats at each of 6 ventricular sites per animal). Timing difference between computed and contact electro-
endocardial plunge-electrode site. Note that there are no systematic directional errors in the location of the RF lesions placed. Average diameter of the RF lesions was 5.8±1.1 mm. Distances from the center and edge of the RF lesions to the plunge electrodes were 4.0±3.2 mm (median, 3 mm) and 1.2±3.2 mm (median, 1 mm), respectively. Figure 7 demonstrates the isotopotential activation maps obtained and subsequent pathological findings after RF lesion placement in 2 experiments. In 2 animals, plunge electrodes were in contact with Purkinje fibers (Figure 8). In both, the site of the RF lesion was at or near the site at which these fibers entered the endocardium. When the latter are used as the sites of earliest activation, the distance from the center and edge of the lesion to the pace-activated site becomes 3.0±2.9 mm (median, 3 mm) and 0.2±2.9 mm (median, 0 mm), respectively. In 11 of 17 lesions, there was an increase in pacing threshold, and there was a complete loss of capture in 2.

**Discussion**

The EnSite system, which includes the array catheter and computerized mapping system, demonstrated excellent accuracy in locating a driven electrode during in vitro tank testing at distances ≤50 mm from the array, whereas accuracy at >50 mm was less. In vivo testing in the canine LV demonstrated the capability of the system to produce noncontact electrograms that are highly correlated to contact electrograms in terms of both activation timing and morphology. Thus, the system was demonstrated to accurately map endocardial activation of the entire canine LV in a single beat. Finally, using activation mapping and locator function, we accurately directed an EP catheter to sites of focal endocardial activation produced by pacing.

**In Vitro Tank Testing**

During testing of the mapping system in an idealized environment, 4 potential causes of error in determining distances between the roving and driven electrodes were identified: (1) difficulty in placing the roving electrode, (2) error in the boundary-element isopotential-map generation such that the resultant electrical field created by the driven electrode was not accurately positioned on the endocardial model, (3) granularity due to the finite number of grid vertices (3360) on which endocardial sites can be labeled, and (4) error in locator positioning of the roving electrode. Although there were some minor difficulties in placing the roving electrode at the desired location, the majority of error identified related to grid granularity as the distance from the array catheter exceeded 5 cm. (Distance between grid vertices increases as the radial distance from the array catheter increases.) This error was compounded because only grid vertices and not areas between were used to label the focal potential created by the driven electrode. Corrections, which are being developed, include supporting map labels everywhere rather than only at grid vertices.

**In Vivo Comparison of Computed and Contact Electrograms**

The mapping system was very good at computing electrograms that closely matched those recorded from the endocardial surface both in timing and in morphology. Importantly, the electrograms for these comparisons needed to be accu-
rately located anatomically. Thus, the accurate reconstruction of electrograms simultaneously tested both the boundary-element inverse solution as well as locator functionality (including ability to reconstruct chamber geometry).

In Vivo Studies Locating Site of Endocardial Pacing
Locating point pacing sites on the endocardial surface uses many of the features of this new technology. Using the locator

Figure 7. Top left, Color-coded (white [most negative] to purple [most positive]) isopotential map of LV endocardium with activation spreading from site of local pacing by plunge electrode. Superimposed grid vertices represent projected 3360 electrical potential sites. Green line is locator signal indicator and demonstrates that the location of EP-catheter tip used to apply RF lesion was just off the center of first activation. During placement, the EP catheter repeatedly slipped off the site of earliest activation. Top right, At autopsy, the RF lesion was just on the other side of a ventricular trabeculation from location of the endocardial pacing site. Bottom left, Color-coded activation map. By use of the locator function, the EP-catheter tip was placed directly on the site of earliest pacing-induced activation. Application of RF energy resulted in loss of pacing capture. Bottom right, Subsequent autopsy demonstrated inclusion of the plunge electrode within the radius of the RF lesion.

Figure 8. Photographic illustration of Purkinje fibers in contact with endocardial pacing electrodes (A). The site of RF lesion is located (B) where these fibers enter the myocardium.
function, a separate EP catheter could be placed at these sites with ease and accuracy. Physical access to sites despite anatomic obstacles, such as papillary muscles, was supportive of system accuracy, despite the fact that these obstacles hindered placement of the EP catheter. There was no systematic error in RF lesion location with respect to either endocardial pacing site location or position of the pacing site in reference to the array.

Study Limitations
The in vitro studies used an idealized chamber. In vitro testing with more complex chamber shapes may be useful in the future. Although the ability to accurately reconstruct chamber geometry was not independently validated in our studies, indirect evidence supports the accuracy of the system. First, the locator system performed well in the tank environment, and second, the ability to reconstruct electrograms and locate endocardial pacing sites in the animal studies required accurate chamber geometry reconstruction. In the animal studies, electrogram waveform morphology and timing comparisons were performed during sinus rhythm. Comparisons of electrograms during ventricular tachycardia were not performed. The focally paced and activated model used created local activation in otherwise healthy tissue. Because clinical ventricular tachycardia often does not involve a focal etiology and occurs in diseased tissue, the clinical relevance of these studies must be viewed accordingly.

Comparison of the EnSite System With Other Catheter-Based Techniques of Electroanatomic Endocardial Mapping
Attempts to accurately map the LV endocardial surface originated with single catheters used to sequentially map point by point. Anatomic location has been crudely assessed by use of fluoroscopy. Attempts to increase the number of simultaneously mapped sites include increasing the number of electrodes on each catheter, increasing the number of catheters, and creating different catheter shapes. None of these techniques allow for rapid and anatomically accurate mapping of the entire endocardial surface. Furthermore, the ability to guide an additional EP catheter to a specific site can be impeded by the presence of other catheters used in the mapping process.

Using a special catheter containing a magnetic field sensor along with a magnetic field emitter located beneath the patient table (Carto, Biosense), Gepstein et al created anatomically accurate global activation maps. Activation maps were sequentially constructed by use of contact electrograms from the catheter tip. The obvious limitation of this approach is that because the acquired data are not coherent in time, multiple beats are required for creation of the activation map. Thus, a stable rhythm and hemodynamic tolerance are required during map acquisition. Another limitation is the required special catheter containing a magnetic field sensor.

Khoury et al reported mapping endocardial activation using a multipolar, olive-shaped, noncontact probe in isolated perfused canine LV. Using a boundary-element inverse solution, they reported good results in locating a paced activation site. However, they noted a 10° rotational error in defining the position of the probe relative to the endocardium, which yielded an 11-mm error in locating the paced site. The reconstructed potentials were noted to be sensitive to errors in geometry and probe position, but the spatial characteristics (locations of maxima and minima) were fairly accurate. Recently, this work was expanded to include an in situ study in a single dog. Serial transeptal endocardial echocardiographic images were used to reconstruct LV internal geometry. Accurate chamber reconstruction was demonstrated to be a prerequisite to reconstruct endocardial potentials.

Accurate reconstruction of chamber geometry is required for noncontact mapping. In the system used in the present studies, the same array and EP catheters provided input to both anatomic (locator) and electrophysiological functions, thereby largely eliminating any rotational error. For example, if a 10° rotation were imposed on the array, then a given site would be rendered in a rotated position. Accordingly, a catheter tip viewed with the locator would still be appropriately guided to the now-rotated site. Furthermore, the stability of the array catheter (with the tip seated in the LV apex) contributed to the accurate location of sites in these studies. Finally, the array catheter, by virtue of its noncontact position, allows placement of a separate EP catheter to endocardial sites without significant difficulty.

Conclusions
The EnSite System, which includes the noncontact balloon multielectrode array catheter and computerized mapping system, provides anatomically accurate endocardial isopotential mapping during a single cardiac cycle. Furthermore, the EnSite Guide locator component allows for the accurate and expeditious placement of an EP catheter to sites within the mapped chamber. The creation of global electroanatomic chamber maps, with animated isopotential and isochronal presentations, and the ability to capture the activation pattern of a single beat may advance our understanding and treatment of human cardiac arrhythmias.

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