Catheter mapping and ablation are increasingly performed for complex arrhythmias that require a complete understanding of mapping techniques to identify the arrhythmia substrate. In this session of Teaching Rounds, we begin a 3-part series that focuses on key issues related to 3-dimensional electroanatomic mapping.

The general principles, rationale, and working of the various mapping systems have been explained well in the existing literature. In brief, these systems use an electromagnetic or impedance-based catheter location method that allows creation of a 3D anatomic shell of the cardiac chamber of interest. During mapping, the electrogram obtained at a given site is stored and the activation time catalogued as the catheter moves across the chamber of interest and the timing of these electrograms are compared with a predetermined reference. As this process continues, a color scheme is assigned to an isochronal color scale based on their respective activation times. In addition to the activation map, maps that display the voltage of the recorded electrograms can be created. For successful interpretation of these maps, a variety of considerations must be understood and meticulously managed. Good catheter contact, correct interpretation of the colors in the map, appropriate choice of reference electrogram, complete mapping of the correct chamber of interest, and strategies to address catheter tip migration with respiration or change in cardiac rhythm must be correctly chosen for the map to identify the successful ablation site as a red region, indicating the earliest activation. At sites where ablation of focal tachycardia is successful, the earliest bipolar electrogram in the “red region” will precede the QRS or P wave by at least 20 to 30 ms and have a QS complex in the unipolar electrogram.

On the other hand, when the arrhythmia is due to a large reentry circuit, as in scar-related ventricular tachycardias and atrial macroreentrant tachycardia, interpretation of color-coded activation sequences requires more caution. First, with reentrant tachycardia, there is no absolute early or late site because any given area of activation will have other sites that are activated before or after that location. If the entire reentry circuit is completely mapped, the red area of earliest activation will be adjacent to a purple area of latest activation, because the circulating wave front moves from the purple region back into the red region to complete the circuit.

Does the red site mean anything at all? In Figure 1, an electroanatomic map of a macroreentrant left atrial tachycardia is shown. Illustrated is the effect of changing the time of the point of reference (choice of reference electrogram). Changing the selected reference time changes the location of the red region. Thus, the same tachycardia mapped by 2 different operators, both of whom chose 2 different but appropriate reference electrograms for the map, may have a very different appearance. If the annotation is correct, however, the sequence of activation from region to region will be the same.

In addition to selecting a reference point, electroanatomic mapping systems also require that a window of interest for mapping be selected. This window is defined by specifying an interval preceding and after the reference point that thereby determines the position of the reference point in the

Teaching Rounds in Cardiac Electrophysiology

Three-Dimensional Mapping of Cardiac Arrhythmias
What Do the Colors Really Mean?

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Received October 8, 2010; accepted October 18, 2010.
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(Circ Arrhythm Electrophysiol, 2010;3:e6-e11.)
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Circ Arrhythm Electrophysiol is available at http://circep.ahajournals.org
DOI: 10.1161/CIRCEP.110.960161
Figure 1. Two electroanatomic activation maps of the same macroreentrant left atrial tachycardia (left atrial flutter) created with 2 different temporal references are shown. In each panel, orientation of the left atrium is indicated by the orientation of the face at the top of the panel and the small heart in the lower left corner. A through E, “Earliest” activation (red) is seen in the roof of the left atrium and then proceeds down the septal and lateral walls, with latest activation at the inferolateral left atrium. A’ to E’ show the same tachycardia, but the map is constructed based on a reference point that is 120 ms later than selected for A through E. Notice that the activation sequence has significantly changed, with “earliest” activation (red region) at the inferior portion of the left atrium.

window. Figure 2 illustrates the effect of changing the window of interest on the color coded activation times. For reentrant tachycardias, this window is typically specified such that the sum of the intervals approximates the tachycardia cycle length (see below), but the window settings specifying how much of the cycle length being mapped should be shown as being before or after a particular reference electrogram is arbitrary. Two different operators may correctly choose 2 different windows of reference, again giving rise to 2 different locations for “red areas” for the same tachycardia. From these considerations it is clear that the red or “early” site is an entirely arbitrary location for macroreentrant arrhythmias and should in no way influence where radiofrequency energy should be delivered.

The “exit site” of a reentrant tachycardia is often taken to represents the transition site between diseased myocardium housing critical components of the reentrant circuit and the exit of the wave front to the bulk of relatively normal myocardium. The exit site probably determines the surface ECG morphology (p wave or QRS), and activation of this region precedes the onset of the QRS or P wave in the surface ECG. Does the red area of an electroanatomic map represent the exit site? As is clear from the examples above, the location of the red “early” region is dependent on the settings for the reference electrogram and mapping window of interest and does not necessarily identify the reentry circuit exit. If, however, the QRS or P-wave onset is clearly defined, the window of interest can be specified such that the red region indicates activation immediately preceding the QRS or P-wave onset, consistent with the exit region. In some tachycardias, the entire reentry circuit with activation spanning the entire tachycardia cycle length cannot be identified. Portions of the circuit may be intramural or epicardial or generate low-amplitude electrograms that cannot be detected by the recording system. In those circumstances, the 3D map essentially identifies the “focal” exit site of the tachycardia.
circuit in that chamber. If this is the circuit exit, pace mapping at that site typically resembles the tachycardia. Understanding this possibility, however, it should be remembered, as emphasized above, that when dealing with a reentrant tachycardia, the color scheme alone is not a sufficient guide to choose appropriate ablation sites.

**Conduction Velocity**

Reentrant tachycardias are often supported by a region of slow conduction. Valuable information about conduction velocity may be gleaned from the color activation map. Each color shift represents a temporal fraction of the entire tachycardia cycle length. Thus, multiple colors evident over a small distance in the heart suggest a region of slow conduction.

Interpreting color maps to ascertain conduction velocity assumes, however, that the wave front of activation is propagating roughly linearly through the region from the earlier side to the later side. That is, along the vector of the color changes. This is, however, not always the case. For example, in bystander areas of slow conduction or when adjacent areas are separated by conduction block, the wave front may reach adjacent locations from different paths. This creates a “pseudointerval” between each of these isochrones that may give the false appearance of slow conduction or the appearance of conduction when there is block between regions. This potential pitfall is influenced by the “fill threshold.” Mapping systems assign an activation time over the area around an acquired point. The size of this area is determined by setting the “fill threshold.” If inadequate numbers of points are taken and the fill threshold allows interpolation over a large area, the colors will not represent a true picture of either conduction velocity or activation sequence and the anatomy may also be distorted (Figure 3).

From these considerations, it is clear that interpreting color activation maps is facilitated by knowledge of the likely arrhythmia mechanism: focal or reentrant. Regardless of mechanism, however, the operator should consider whether a sufficient number of points have been taken to adequately define activation and anatomy and whether the reference electrogram and window of interest have been appropriately selected.

**Have You Taken Enough Points?**

There is no definitive answer to this question. The required number of points needed to construct a reliable map is dependent on many factors including tachycardia mechanism, size, and geometry of the chamber being mapped and the potential involvement of other chambers that may need to be mapped. In addition, the number of points that can reasonably
be obtained may be limited by the hemodynamic stability of the patient and stability of the arrhythmia. In our laboratory, we generally take approximately 100 points for automatic tachycardias and 200 points for reentrant arrhythmias in a given chamber. More important than this arbitrary number is the need to be certain of the completeness of the map in terms of chamber geometry. Expected anatomic boundaries such as the vena cava, great arteries, and atrioventricular annuli should be included in the map. Causes for incomplete chamber mapping include an inappropriately placed reference point.

Figure 3. Three-dimensional activation maps of a right ventricular focal ventricular tachycardia. A through C. From top to bottom, the right ventricle is viewed from different perspectives. Earliest activation (red) is at the leftward superior aspect of the right ventricular outflow tract, where ablation was performed (dark red circular tags). Activation spreads away from this focal red region in all directions.

Right-sided frames in each panel (A’ through C’) have a larger fill threshold, extrapolating each activation time to a larger area than the counterpart left frames (A through C). Thus, A’ through C’ show no gaps between points; areas without acquired points have been artificially filled by the software, which has assigned different hues of color to the gaps where no points where acquired, obscuring the fact that data for these regions are missing. Tachycardia cycle length was 432 ms; the activation time during mapping covered 136 ms before (number at the top above the red section of the color code bar) to 32 ms after (number at the purple region of the color code bar). Thus, activation times account for a total 168 ms, which is less than 40% of the tachycardia cycle length of 432 ms, consistent with a focal origin tachycardia.
patch (such that some points, for example, taken in a very large ventricle, will not appear in the map), diverticula, aneurysms, or pouches that have not been entered and yet may house the arrhythmogenic substrate and the need for specific epicardial mapping. Even with an automatic tachycardia, a complete map is desirable. For example, an unexpectedly early ventricular endocardial site separate from another early site could be an important clue to a fascicular origin of arrhythmia (exiting to two sites from the Purkinje system) or the true early site of activation being epicardial or in another chamber.

Choosing an Appropriate Reference
With atrial tachycardias, a stable intracardiac atrial electrogram is usually chosen because the P wave can be indistinct. The characteristics of a good reference electrogram include stable catheter position at that site (screw-in electrodes can be used in the right atrium to achieve stability) and avoiding use of sites with multicomponent signals that may cause the system to automatically select a different electrogram peak on the reference electrogram for different beats. With ventricular tachycardia, a large, reproducibly identifiable component of a QRS complex is typically chosen.
Window of Interest Selection

For focal tachycardias, the window of reference does not have to be precisely chosen. Anticipating that the true early site of activation is rarely earlier than 50 ms from the start of the surface ECG (P wave or QRS) and appreciating which component of the ECG or specific electrogram is being chosen, one can quite easily choose how much earlier than the reference the window should start. For example, if a focal ventricular tachycardia has a total QRS duration of 180 ms, a window that begins 300 ms before the peak QRS should be more than sufficient to identify the earliest site. With a focal left atrial tachycardia in a normal heart, activation beginning 160 ms earlier than a coronary sinus activation site probably would be sufficient. On the other hand, with a focal atrial tachycardia arising from the right atrium in a patient with a diseased heart and slow intra-atrial conduction, the earliest site of activation could be close to 300 ms earlier than a lateral coronary sinus reference site, and the beginning of the mapping window should exceed this time interval (Figure 4).

Significantly more consideration is required when choosing the window of interest for reentrant tachycardias. Generally, the window of interest is chosen to be 10 or 20 ms less than the tachycardia cycle length. If the window is too short, the entire cycle length cannot be mapped, and 2 different points in the circuit may be catalogued with similar timing (for example, a tachycardia cycle length 300 ms, total window of interest 200 ms starting 100 ms before and ending 100 ms after the reference point, points that 210 to 250 ms ahead of the earliest site could all appear with the same red color annotation). On the other hand, if too large a window of interest is chosen, 2 electrograms representing activation of the same site may appear within the window of interest. If the operator does not consistently take either the earliest or later electrogram, an entirely meaningless map will be created.

Disclosures

None.

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Key Words: ablation ■ mapping ■ arrhythmia ■ radiofrequency ■ carto ■ electroanatomic mapping
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*Circ Arrhythm Electrophysiol.* 2010;3:e6-e11
doi: 10.1161/CIRCEP.110.960161

*Circulation: Arrhythmia and Electrophysiology* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-3149. Online ISSN: 1941-3084

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