ATRIAL FIBRILLATION

RESEARCH ARTICLE

Analysis of Far-Field Electrograms to Identify the Slow Conduction Zone in Right and Left Atrial Flutter

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ABSTRACT. In atrial flutter, the circuit often contains a site of slow conduction that functions as a critical isthmus. We applied the piecewise linear adaptive template matching (PLATM) mapping algorithm to identify the slow conduction zone (SCZ) of the reentrant circuit. PLATM evaluates timing in the expansion or contraction of far-field electrogram deflections in response to cycle length changes. Electrogram data were analyzed from 20 patients with atrial flutter (14 right atrial, six left atrial) as confirmed by entrainment and activation mapping. At each electrode location, delay of far-field electrograms during cycle length prolongation in flutter was analyzed to estimate the relative timing of SCZ electrical activation with respect to local activation at the recording site. Estimation of SCZ activation from the distant recording sites was considered to be successful when the difference between estimate and actual SCZ activation time was within ±20 ms, the resolution of the method. The SCZ was localized to the site of termination during ablation in 15 of 20 patients (75%) with atrial flutter. PLATM was not usable when cycle length variation during atrial flutter was <10 ms (three cases) or when the far-field signal was not readily evident above the noise floor (two cases). Delays or advances in far-field deflections in the recorded electrogram can be related to, respectively, slowing or accelerated conduction in the isthmus region during atrial flutter, without requiring overdrive pacing. Prospective study of PLATM will be necessary to validate its potential complementary role in conjunction with existing techniques for catheter ablation guidance.

KEYWORDS. atrial flutter, catheter ablation, electrograms, PLATM, slow conduction zone.

Introduction

Catheter ablation for cavo-tricuspid isthmus (CTI)-dependent atrial flutter consists of interruption of the flutter circuit by creating a line of conduction block between the tricuspid annulus and the inferior vena cava. Ablation for CTI-dependent flutter is highly efficacious, with long-term freedom from atrial flutter well over 90% in different studies. By contrast, left atrial flutter and atypical right atrial flutter comprise numerous potential circuits without a uniform, well-defined anatomic region for successful treatment. Mapping and ablation of atypical atrial flutter are lengthier than similar procedures for CTI-dependent flutter and are associated with lower efficacy. The CTI has been characterized as an area of slow conduction during CTI-dependent flutter. Tai and colleagues showed in 24 patients with CTI-dependent flutter that conduction time in the CTI accounted for approximately 40% of the flutter cycle length. Slowing of the flutter cycle length with procainamide infusion resulted in an increase in conduction time at the isthmus that accounted for 52% of the increase in overall flutter cycle length. Thus, slow conduction during atrial flutter, and greater influence on changes in flutter cycle length,
are characteristics that uniquely identify the isthmus in CTI-dependent flutter. Similarly, an isthmus of slow conduction has also been identified in left atrial flutter, in atypical right atrial flutter, and in atrial flutter after surgery for congenital heart disease. The existence of a slow conduction zone (SCZ) at the isthmus of macro-reentrant atrial flutter that influences overall cycle length suggests that measurement of far-field deflections could be useful for localizing the isthmus in atrial flutter, as has been demonstrated in reentrant ventricular tachycardia in both canine and human studies. In this study, we analyzed atrial far-field electrograms to estimate the timing of activation of the slow conduction zone during atrial flutter, to help identify the isthmus site suitable for catheter ablation.

Methods

This study was approved by the Institutional Review Board at Columbia University Medical Center. Intracardiac electrogram data were retrospectively analyzed from 20 patients in total, 14 with CTI-dependent flutter and six with left atrial flutter. Each patient had a single flutter circuit confirmed by entrainment and activation mapping, and the flutter terminated during RF ablation in all patients. Among the six left atrial flutter cases, three flutters terminated during ablation at the left atrial roof and three terminated at the mitral isthmus.

For cases of CTI-dependent flutter, a 20-pole catheter with 2-8-2 mm interelectrode spacing (Halo XP, Biosense Webster, CA) was positioned in the right atrium, encircling the tricuspid annulus. An octapolar catheter with 2-5-1 mm spacing (EPXT Octapolar Steerable Catheters, C. R. Bard, Inc., Murray Hill, NJ) was placed in the coronary sinus, with the most proximal bipole at the coronary sinus ostium. A bipolar mapping/ablation catheter with 2-5-2 mm spacing (Thermocool, Biosense Webster) was positioned between the tricuspid annulus and the inferior vena cava. For cases of left atrial flutter, an octapolar catheter with 2-5-1 mm spacing (C. R. Bard, Inc.) was placed in the coronary sinus, and a roving bipolar mapping/ablation catheter (Thermocool, Biosense Webster) was positioned to collect electrogram data at sites including the left atrial roof, posterior and anterior left atrium, mitral annulus below the left inferior pulmonary vein, and left atrial septum. A schematic of the locations of the data collection sites is shown in Figure 1. All signals were filtered (passband: 30–500 Hz) to remove baseline drift and high frequency noise, sampled at 977 Hz, and stored on digital hard drive and archival media. The digitized signals were subsequently analyzed retrospectively with MATLAB (Mathworks, Inc., Natick, MA) and computer programs that were developed by one of the authors (EJC).

Explanation of PLATM

Far-field electrograms were analyzed based on the method of piecewise-linear adaptive template matching (PLATM). PLATM utilizes a mean squared error approximation to detect changes in far-field electrogram deflections over many cardiac cycles that tend to be concentrated at the SCZ. Increasing delay in far-field deflections over many cardiac cycles (expansion) corresponds to deceleration of the activation wavefront in the SCZ, which causes cycle length prolongation because the activation wavefront is constrained. Advancement of far-field deflections corresponds to acceleration in the SCZ, which causes cycle length shortening. The SCZ of the reentrant circuit is the critical region in which such changes can occur in the infarct border zone of the left ventricle, because the activation wavefront is constrained by arcs of conduction block and so cannot go around. As a first approximation, it was supposed that the isthmus of atrial flutter is a similarly constrained three-dimensional structure. Within the SCZ itself, during cycle length prolongation it would be expected that symmetric expansion of the electrogram would occur immediately prior to, during, and after local activation as slowing is occurring locally. In order for PLATM to be applied in this analysis, between 20 and 60 s of electrogram data were collected continuously at each site of catheter contact during atrial flutter. An absolute change in flutter cycle length of approximately 10 ms or more during the period of electrogram collection was required in order to detect changes in far-field activation that would allow for use of the algorithm.

At each electrode location, delay or advancement of far-field electrograms during cycle length changes in flutter were analyzed to determine the relative timing of the SCZ with respect to local activation. The time interval from local activation at each recording site to delayed...
far-field deflections was measured and tabulated. The mean difference between this interval, and the actual time of activation of the SCZ of the macro-reentrant circuit as determined by mapping of the isthmus site, was calculated as the error. Estimation of SCZ activation from distant sites was considered to be successful based on agreement with activation and entrainment mapping to within $\pm 20$ ms (the estimate is defined as the mean value pooled from all sites in which far-field deflections were evident), which was the approximate resolution of the method determined from ventricular data.\textsuperscript{14} Supposing a typical conduction velocity of 0.5 mm/ms, an error of $\pm 20$ ms corresponds to an estimated distance to within $\pm 1$ cm of the actual isthmus location. The activation time at each isthmus as determined by entrainment and activation mapping was compared with the midpoint of largest delay or acceleration in far-field deflections, according to the PLATM algorithm. The proportion of cases in which the SCZ using PLATM corresponded to the isthmus as determined by activation and entrainment mapping was calculated separately for CTI-dependent flutter and left atrial flutter. Reasons for unsuccessful outcomes of PLATM (noisy signals and/or lack of changes in cycle length) were also tabulated.

**Results**

In the cases used for this study, cycle length prolongation in atrial flutter and the resulting delays in far-field deflections were used for the PLATM algorithm. An example of the delay in the far-field signal caused by deceleration of conduction at the SCZ during atrial flutter is shown in Figure 2. In this figure, the signal from a bipolar electrode of the catheter encircling the tricuspid annulus (Halo 4) was segmented by successive cardiac cycles and overlapped. Colors from red, to yellow, green, blue and violet designate sequentially later cardiac cycles, with 22 cycles shown; each color designates four to five cycles. The electrogram segments are aligned based upon the maximum peak, which is shown as occurring at time $= 0$ ms as a reference. There is a delay in the far-field deflections (smaller deflections away from the main peak) beginning at 80 ms following local activation (bar). After 100 ms, there is no further expansion between electrograms. It is evident that many, although not all, of the later electrograms (colored blue and violet) have shifted to the right (delayed) after 100 ms, as compared with the electrograms occurring on earlier cardiac cycles colored red, yellow, and green. Thus, it would be expected that delay in the SCZ during atrial flutter begins 80 ms following local activity at this site and continues to approximately 100 ms on the scale. The largest difference from earliest (red) to latest (violet) cardiac cycle is about 10 ms, which is therefore the maximum delay caused by deceleration of the activation wavefront in the slow conduction zone. Assuming an average conduction velocity of 0.5 mm/ms, we would expect the isthmus SCZ site to be located approximately:

$$80 \text{ ms} \times 0.5 \text{ mm/ms} = 4 \text{ cm}$$

By following the wavefront in the prograde direction from the recording site, this distance would coincide with the location of the CTI as determined by electroanatomic mapping. Figure 3 shows the location of recording sites and times, and anatomic locations in this patient. The flutter cycle length was 240 ms, and recording times were referenced to activation in the distal pole of the ablation catheter at the CTI. According to the mean far-field delay at all recording sites, the slowing event began 15 ms prior to (or 225 ms after) local activation when using the ablation catheter around the tricuspid annulus (Halo), with slowing event associated with electrogram expansion, occurring at 80–100 ms following local activation (denoted by bar).
catheter as a fiduciary point of 1 ms. This is in agreement with the time from local activation at the H4 halo site (149 ms) i.e. \( \approx 80 \text{ ms} \) from activation of H4 to activation of the SCZ.

Figures 4a and 4b display electrogram tracings from a case of left atrial flutter that was ablated at the mitral annulus. Recordings from the distal ablation catheter at the left atrial roof (4a) do not reveal any electrogram expansion, but at the recording site between the mitral annulus and the left inferior pulmonary vein (4b), a slowing event is discernible approximately 50 ms prior to local activation. Thus, for the recording site of Figure 4b, the isthmus SCZ would be anticipated to reside approximately:

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50 \text{ ms} \times 0.5 \text{ mm/ms} = 25 \text{ mm} \]

in the retrograde direction along the circuit.

Summary statistics

Among all 20 patients with atrial flutter, average age was 62 years (range 45–74), and four patients (20%) were female. Among the 14 patients with CTI-dependent
flutter, counter-clockwise flutter was present in 12 (86%), and the average cycle length was 241 ± 33 ms. Atrial flutter was induced in four (29%) cases and was present at the start of the electrophysiologic study in eight cases (71%). Among the six patients with left atrial flutter, five had a prior history of ablation for atrial fibrillation. Mitral isthmus flutter was present in three patients and roof flutter was present in three patients. Average cycle length was 251 ± 17 ms. Flutter was induced in four cases (66%) and was present at the initiation of the electrophysiology study in two cases (33%).

Table 1 illustrates the outcome of PLATM for all right and left atrial flutter cases. Among 14 right atrial flutter cases, PLATM correctly identified the SCZ at the CTI in 11 (78%). In three cases, PLATM could not be used either because the degree of cycle length prolongation was <10 ms (two cases) or no discernible far-field signal could be identified above the noise background (one case). In the six left atrial flutter cases, PLATM correctly identified the isthmus in four cases (66%). In one case, the algorithm could not be used because the degree of cycle length prolongation was insufficient, and in one case the far-field signal was not identifiable above the noise background. The mean number of recording sites at which far-field signal was evident and PLATM could be used per patient was 5.9 ± 4.7 of 11.6 ± 3.9 total recording surface sites (including CS, Halo, Lasso, ABL proximal and distal, when they were recorded). Thus, at an average of 50.9% of recording sites per patient, the approximate time difference between local electrical activity and activation of the slow conduction zone in the circuit was determinable.

Discussion

In this study, we applied a technique to identify the SCZ of a reentrant arrhythmia to the problem of atrial flutter and found that it is feasible in a manner similar to its prior use in ventricular tachycardia. Our findings suggest that the isthmus of a flutter circuit can be identified through changes in the timing of far-field electrograms as they result from overall tachycardia cycle length changes. The PLATM algorithm can thus potentially provide a complementary mapping solution, particularly for cases of non-CTI-dependent right atrial flutter, and left atrial flutter in which mapping and ablation are more difficult and time-consuming.

Mapping strategies for atrial flutter have often included the use of activation mapping or entrainment mapping. When activation mapping is used, activation sequences during atrial flutter are compiled from electrode recordings at many atrial locations. The sequence of activation of the flutter circuit is constructed in three-dimensional space and an ablation strategy is devised in order to target the isthmus of the circuit, in which the electrical impulse is constrained. One potential pitfall of activation mapping is that atrial flutter circuits may occur with multiple simultaneous circuit loops, making it difficult to discern a critical isthmus of the circuit for ablation. Inaccurate marking of points on the activation map can incorrectly summarize the apparent path of a flutter circuit. Thus activation mapping, besides being time-consuming, is subjective and not necessarily reproducible from one investigator to another.17

Entrainment mapping involves the use of overdrive pacing in order to repeatedly reset a reentrant arrhythmia circuit.18 During entrainment, the pacing stimulus enters the excitable gap of the reentrant circuit, and travels both orthodromically and antidromically. The orthodromic wavefront captures the circuit and resets it to the paced rate, traveling around the circuit and colliding with the wavefront of the next paced beat. When the pacing train is stopped, the time it takes for the wavefront of the circuit to return to the pacing electrode (postspacing interval) indicates the distance of that site from the reentrant circuit. In general, a postspacing interval that exceeds the tachycardia cycle length by 20 ms or less indicates that the pacing site is a part of the circuit.7 However, it is not always clear from entrainment attempts that the arrhythmia has actually been entrained during overdrive pacing. Another important problem with entrainment is that flutter may terminate or transform to a different flutter circuit during the overdrive pacing that is required by entrainment mapping. This occurs in as many as 50% of entrainment attempts,7 and it requires that the original circuit be re-induced, which is sometimes not possible at the time of electrophysiology study.

Potential advantages of the PLATM algorithm for mapping of atrial flutter include the fact that overdrive pacing is not required, so that the chance of inadvertent termination of the arrhythmia is reduced. In addition, the identification with PLATM of those areas that directly influence overall flutter cycle length, in terms of time of activation with respect to local activity at the recording site, increase the chance that an isthmus supporting the perpetuation of the arrhythmia is detected, rather than a bystander site of slow conduction.

However, several limitations of PLATM and of our analysis should be noted. Application of PLATM requires a trend in change in cycle length of at least 10 ms (prolongation or shortening) over the course of the
electrogram recording period. Most of the difficulty with applying PLATM in this study resulted from a lack of cycle length variation in the tachycardia. Future studies could investigate the utility of antiarrhythmic medications such as procainamide to reduce conduction velocity in the SCZ so that the algorithm could be used even when changes in velocity do not normally occur. Additionally, the spatial resolution of PLATM depends in part on whether far-field deflections are detectable, which, in turn, depends on the orientation of the recording bipolar electrode, the electrode dimensions, wavefront orientation, and the volume of tissue activating per unit time. However, as we have shown in this study, when electrograms are recorded from a multiplicity of sites, far-field deflections pertaining to the SCZ are evident in about half (see Results). Another limitation is that in this study PLATM was always applied to macro-reentrant flutter, but probably could not resolve any isthmus present in micro-reentry due to the microscopic size of the circuit components and the negligible far-field signal that would be generated. Furthermore, the analysis we presented here was retrospective, and the development of a real-time algorithm is necessary in order to test the utility of PLATM prospectively. Nonetheless, our results indicate that the algorithm, based on physiologic characteristics of reentrant circuits, has potential application particularly to the difficult problem of atypical flutter.

References