An Algorithm to Predict the Site of Origin of Focal Atrial Tachycardia

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Background: Only a few algorithms for predicting the site of origin of focal atrial tachycardia (AT) have been reported. We aimed to develop a new and more effective algorithm.

Methods: Surface 12-lead electrocardiograms were collected during tachycardia and sinus rhythm in 61 patients who received successful radiofrequency ablation. P-wave polarities, durations, and amplitudes were analyzed. Predictive values of the most significant parameters were determined. An algorithm was then developed and prospectively evaluated in 30 new consecutive AT patients.

Results: Thirty-six percent (22/61) of the foci were located at the ostium of coronary sinus (CS). Other common foci included pulmonary veins (PVs, n = 15), right atrial appendage (RAA, n = 7), parahisian area (n = 7), and crista terminalis (CT, n = 3). Positive P waves in inferior leads (II, III, and aVF) and a negative P wave in lead aVR indicated high atrial origins (high CT, superior PVs, and RAA, defined as Area A), with a sensitivity of 95% and a specificity of 90%. Negative P waves in inferior leads and a positive P wave in lead aVR suggested right low septal origins (CS ostium and inferior tricuspid annulus, defined as Area B), with good sensitivity and specificity (88% and 89%, respectively). This new P-wave diagnostic algorithm correctly identified the site of origin in 90% of AT cases.

Conclusion: Combination of data from multiple leads and regrouping of sites of origin provides a better predictive value. (PACE 2011; 34:414–421)

P-wave morphology, focal atrial tachycardia, site of origin, prediction

Introduction

Atrial tachycardia (AT) is one of the more common supraventricular tachycardias. The foci of origin of ATs are distributed throughout the atria. The crista terminalis (CT), coronary sinus (CS) ostium, atrial septum, and pulmonary vein (PV) are the most common foci.1–6 These forms of AT can be cured by radiofrequency ablation (RFA). To simplify the procedure and reduce the x-ray exposure time, accurate prediction of the site of origin of AT by analyzing surface P waves is advisable before procedure.

The purpose of this study was to develop and prospectively evaluate a new algorithm to localize the particular origin of AT through detailed analysis of P-wave morphology (PWM) in the 12-lead electrocardiogram (ECG).

Ethical Review

The study was approved by the local research ethics committee. All patients provided written consent prior to electrophysiological study and ablation.

Study Population

Between January 2002 and May 2007, 94 patients underwent successful RFA of focal ATs in the Department of Cardiology of the first affiliated hospital of Nanjing Medical University. The distribution of AT origins was: CS ostium (28 out of 94, 29.8%), PVs (17 out of 94, 18.1%), CT (13 out of 94, 13.8%), parahisian area (14 out of 94, 14.9%), right atrial appendage (RAA) (nine out of 94, 9.6%), tricuspid annulus (TA, six out of 94, 6.4%), mitral annulus (MA, three out of 94, 3.2%), left atrial appendage (LAA, two out of 94, 2.1%), superior vena cava (SVC) (one out of 94, 1.1%), and superior fossa ovalis (one out of 94, 1.1%). Of 94 patients, 61 patients who had complete 12-lead surface ECG and clear P waves were retrospectively analyzed to derive a new algorithm. Thirty focal AT patients undergoing RFA between June 2007 and June 2009 were prospectively evaluated using the new algorithm to validate it. All patients had clinically
documented paroxysmal or persistent AT with clear 12-lead surface P waves. For some patients with fast AT over 130 beats per minute, 12-lead surface P waves were collected during the periods of atrioventricular block or after infusion of adenosine or ventricular pacing. Transthoracic echocardiography was regularly performed for the patients before ablation.

**Electrophysiological Study**

Electrophysiological studies were performed in the fasting, nonsedated state. All antiarrhythmic drugs were discontinued for at least five half-lives before the study. Conventional mapping catheters were introduced to the high right atrium (RA), His-bundle area, and CS. Atrial programmed extrastimulation or burst pacing was performed to induce AT. Isoproterenol infusion (2 μg/min) was given to facilitate induction of AT if baseline pacing failed. A diagnosis of AT was made using standard electrophysiological criteria.

**Noncontact Mapping of AT and Ablation Procedure**

Noncontact mapping (Endocardial Solutions Inc., St. Paul, MN, USA) was carried out as described previously. In brief, a 9-Fr 64-electrode balloon catheter was passed over a guide wire into RA or left atrium (LA). Intravenous heparin was infused to keep activated clotting time at 250–300 seconds. By moving the mapping/ablation catheter around the atrial endocardium, multiple spatial points were collected, and a three-dimensional (3D) RA or LA geometry was established. Anatomic structures, including the SVC, inferior vena cava (IVC), RAA, TA, septum, ostium of CS, PVs, and MA, were labeled on the geometry. Using inverse solution mathematics, the software calculated the real-time endocardial potentials simultaneously at more than 3,000 sites and projected them on the 3D geometry. The entire RA or LA endocardial activation was recorded using isopotential color maps and virtual unipolar electrograms at 1–2-Hz high-pass filter setting.

The diagnostic criteria of a focal AT by noncontact mapping are that activation originates from a discrete area within the atrium and spreads simultaneously in multiple directions. The area of earliest activation (EA) was identified on the activation map as the focal point of origin of the tachycardia at the time of the earliest virtual unipolar electrogram, whereas the breakout (BO) point was the site at which activation appeared to spread out toward the rest of the atrium. The EA and BO regions were found to be at the same point in our cases. In addition to the electrophysiological data, the anatomic origins of arrhythmias were defined according to the point position of the mapping/ablation catheter under x-ray projection.

RF application with a target temperature of 45°C and power output of 30–35 W was delivered with normal saline irrigation at 17 mL/min at the EA regions by a radiofrequency generator (IBI, St. Jude Medical, St. Paul, MN, USA). When AT termination was observed during the first 10 seconds, RF delivery was continued to provide a minimum 60-second ablation period. Successful ablation was defined as inability to reinduce AT using the same stimulation protocols.

**Follow-Up**

Patients were followed up on outpatient clinic. Regular resting surface ECG and 24-hour Holter monitoring were performed for each patient.

**PWM Analysis**

Surface 12-lead ECGs were recorded at a speed of 25 mm/s. P waves were classified into four basic types:

1. **positive**: P waves with deviation above the isoelectric line;
2. **negative**: P waves with deviation below the isoelectric line;
3. **biphasic**: P waves having positive/negative and negative/positive deviation;
4. **isoelectric**: P-wave deviation from baseline less than 0.05 mV.

Other characteristics noted were:

1. **Notched P waves**: Those with only double-positive components.
2. **Positive or negative P waves in inferior leads**: These were defined such that P waves in at least two leads of II, III, and aVF were positive or negative.

The amplitude of the P wave was calculated from peak to nadir. Both P-wave duration and amplitude were analyzed. The specificity (Sp), sensitivity (Se), positive predictive value (PPV), and negative predictive values (NPV) for predicting the site of origin were calculated for each P-wave site.

**Development of a New P-Wave Algorithm**

The parameters with high PPVs or NPVs for predicting the sites of origin were determined and selected. A new P-wave algorithm was developed based on the P-wave characteristics of the 61 retrospective patients. The new algorithm was tested and modified in the retrospective patients until the prediction accuracy was at least 90%.
Finally, the prospective performance of the new algorithm was evaluated in a new group of 30 consecutive patients with focal ATs who underwent noncontact mapping and successful ablation.

**Statistical Analysis**

All values were expressed as mean ± standard deviation. Comparison between groups was carried out using Student’s t-test. A χ² test was used to evaluate the ability of each parameter to localize the focus. Differences with P < 0.05 were considered statistically significant.

**Results**

**Clinical Characteristics**

The retrospective study population included 61 patients (29 men) with a mean age of 42 ± 5 years. Echocardiography showed normal LA (33.4 ± 1.5 mm) and normal ejection fraction (63.1 ± 2.3%). Two patients suffered from paroxysmal atrial fibrillation. Two patients were complicated with atrioventricular nodal reentrant tachycardia. Three patients were complicated with left accessory atrioventricular pathways.

The following foci of origin were observed: CS ostium, 22 cases of 61 (36.1%); RAA, seven cases (11.5%); right superior PV (RSPV), five cases (8.2%); left superior PV (LSPV), six cases (9.8%); left inferior PV (LIPV), four cases (6.6%); CT, three cases (4.9%); MA, three cases (4.9%); inferior TA, two cases (3.3%); LAA, one case (1.6%); and superior fossa ovalis, one case (1.6%).

The ventricular rate of tachycardia was 133 ± 9 beats per minute. Two patients suffered from recurrence of AT and received a second procedure at months 5 and 12, respectively. The whole patient group was followed up for 46 ± 5 months.

None of the 15 patients with AT originating at the PV developed complications of PV stenosis after ablation.

**P-Wave Polarities**

The surface P-wave polarities of the tachycardias are shown in Table I. A detailed analysis of each parameter is shown in Table II. Leads aVL and V1 were most sensitive for predicting the right or left AT. A positive P wave in lead aVL was associated with a sensitivity of 91% for right AT. A positive P wave in lead V1 was associated with a sensitivity of 95% for a left AT. However, the specificity was relatively low (79% and 64%, respectively).

For ATs originating from high CT, superior PVs, and RAA (Fig. 1A), P waves were positive in inferior leads and negative in lead aVR. For ATs arising from CS ostium and inferior TA (Fig. 1B), P waves were negative in inferior leads and positive in lead aVL, while the P wave in lead aVR was mostly (21 out of 24) positive. The P wave in
Table II.
Evaluation of Predictive Parameters of P-Wave Morphologies in Surface ECG

<table>
<thead>
<tr>
<th>Parameters in ECG</th>
<th>Site of Origin</th>
<th>Se (%)</th>
<th>Sp (%)</th>
<th>PPV (%)</th>
<th>NPV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive in inferior leads and negative in lead aVR</td>
<td>Area A</td>
<td>95</td>
<td>90</td>
<td>83</td>
<td>97</td>
</tr>
<tr>
<td>Negative in inferior leads and positive in lead aVR</td>
<td>Area B</td>
<td>88</td>
<td>89</td>
<td>84</td>
<td>92</td>
</tr>
<tr>
<td>Positive in aVL</td>
<td>Right atrium</td>
<td>91</td>
<td>79</td>
<td>91</td>
<td>79</td>
</tr>
<tr>
<td>Positive in V1</td>
<td>Left atrium</td>
<td>95</td>
<td>64</td>
<td>55</td>
<td>96</td>
</tr>
<tr>
<td>From negative to positive across the precordial leads</td>
<td>RAA</td>
<td>100</td>
<td>98</td>
<td>88</td>
<td>100</td>
</tr>
<tr>
<td>From positive to negative across the precordial leads</td>
<td>CS ostium</td>
<td>55</td>
<td>95</td>
<td>86</td>
<td>79</td>
</tr>
<tr>
<td>Flat or negative in leads I and aVL</td>
<td>Extreme left origin</td>
<td>79</td>
<td>94</td>
<td>79</td>
<td>94</td>
</tr>
</tbody>
</table>

Area A: High atrial origins, including high CT, superior PVs, and RAA. Area B: Right low septal origins, including CS ostium and inferior tricuspid annulus.

Lead V1 was always positive for left atria origin and always negative for RAA origin. P waves of high CT-originated AT always showed positive-negative (biphasic) variation in lead V1.

For the extreme left foci, including LAA, left PVs, and superior MA, P waves in lead I and lead aVL were negative or low-amplitude positive (Fig. 2). The predictive value of these origins was

Figure 1. P-wave features of high atrial (Area A)-originated and right low septal (Area B)-originated AT. Panel A shows P-wave features for Area A, including high CT, RSPV, and RAA. P waves in inferior leads were positive (thin arrow), and lead aVR was negative (dash arrow). The thick arrows show the characteristic migration from negative to positive for RAA origin. Panel B shows P-wave features for Area B, including CS ostium and inferior TA. P waves in inferior leads (II, III, aVF) were negative (thin arrow), and lead aVR was positive (dash arrow). P waves across the precordial leads are typical (migration from positive to negative in precordial leads for CS ostium and consistently negative P waves for inferior TA, thick arrow).
a sensitivity of 79% and a specificity of 94%. Two patients of superior MA origin showed low amplitude in limb leads and biphasic in precordial leads.

P-Wave Duration

Characteristically, P waves associated with parahisian AT were narrower in most of the 12 leads. Compared with that of CS ostium, lead aVL showed the most significant difference (49.6 ± 8.8 ms vs 71.8 ± 6.9 ms, P = 0.005). Our study suggested that P-wave duration in lead aVL less than 60 ms predicted parahisian origin with an accuracy of 74% (P = 0.008).

Notched P Waves

No notched P waves were detected in right AT. The specificity of notched P waves predicting left atrial origins was 100%; however, the sensitivity was only 26%.

Selection and Regrouping of Predictive Leads

According to the analysis of the PWMs, we found that most of the P waves in inferior leads and lead aVR were consistently opposite, especially for the high atrial and right low septal origins. Positive P waves in inferior leads and negative P waves in lead aVR indicated high atrial origins with a 95% sensitivity and a 90% specificity. Negative P waves in inferior leads and positive P waves in lead aVR suggested right low septal origins with good sensitivity and specificity (88% and 89%, respectively). Consequently, we defined two areas in the atria that had similar ECG patterns:

Area A: High CT, superior PVs, and RAA.
Area B: CS ostium and inferior TA.

As for the adjacent locations of the two defined areas, lead aVR may not be typically positive or negative. For the foci close to Area A, a flat or negative P wave in leads I and aVL can predict extreme origins (Table II). For the foci close to Area B, lower CT-originated AT showed a nonpositive P wave in lead aVR and positive P waves in most of the precordial leads.

Migration feature of P-wave polarities in precordial leads was also found to be specific for prediction of some AT origins. Figure 3 shows the P-wave amplitudes of the PV- and RAA-originated ATs in precordial leads. From lead V1 to V6, PV P waves were always positive but progressively flattened. For the RAA origin, P wave in lead V1 was negative and became progressively positive from V1 to V6. The predictive accuracies were both over 90%. Also the migration from positive to negative in precordial leads was a specific feature of CS ostium-originated AT (Table II). However, we observed three patients with CS

Figure 2. P-wave features of extreme left-side-originated AT. Flat or negative P wave in leads I and aVL (thick arrow), and migration from positive to flat in precordial leads (thin arrow) are the shared features of extreme left-side-originated ATs, such as LAA, LSPV, LIPV, and MA. Broad and notched P waves in lead V1 was the feature of LIPV- and LSPV-originated AT. One mitral annulus-originated AT showed a characteristic biphasic appearance (dash arrow) in precordial leads.
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Figure 3. P-wave amplitude migration in precordial leads for pulmonary vein-originated AT (panel A) and RAA-originated AT (panel B). Panel A shows the migration from positive to flat for pulmonary vein-originated AT. Panel B shows the migration from negative to positive for RAA-originated AT. The circle represents mean value and error bars represent the 95% confidence interval.

ostium-originated AT with all negative P waves in precordial leads similar to that of inferior TA-originated AT.

Creation of a New P-Wave Algorithm and Prospective Application

Based on the tabulated PWMs (Table II), a new algorithm was created to predict the sites of origin (Fig. 4). The algorithm was prospectively applied to a new population of 30 consecutive patients (18 men, mean age of 36 ± 6 years, no structural heart disease) with focal AT. Twenty-seven origins were correctly identified as follows: high CT (six cases); lower CT (two cases); CS ostium (six cases); inferior TA (three cases); RAA (four cases); RSPV (one case); LSPV (two cases); LAA (one case); and parahisian (two cases). The algorithm incorrectly suggested a high CT location for a tachycardia originating in the SVC, a parahisian location for a tachycardia at the left septum, and a RAA location for a tachycardia at the middle TA. Overall, the predictive accuracy of our new algorithm was 90%.

Discussion

By retrospectively analyzing surface PWMs of focal AT patients and using data from multiple leads and reclassifying the foci, a new algorithm to predict the location of AT origin was developed. The predictive accuracy of this new algorithm assessed by prospectively testing 30 new patients was up to 90%.

Tang et al. developed an algorithm to distinguish left and right atrial foci, and pioneered the prediction of focal ATs using surface P waves. They reported that a positive P wave in lead V1 was associated with 93% sensitivity and 88% specificity for tachycardia arising from the LA. A positive or positive-negative (biphasic) P wave in lead aVL was associated with 88% sensitivity and 79% specificity for tachycardia originating in the RA. However, the predictive value of a single lead for differentiating between foci is limited and sometimes the prediction may be incorrect. For example, a positive P wave in lead aVL may occur for RSPV-originated foci, and a positive P wave in lead V1 for foci of CS ostium is not uncommon.

Kistler et al. analyzed 130 pieces of AT ECGs and developed an algorithm with an accuracy of 93% to locate a particular focus by prospectively predicting 30 new ATs. In the first step of their algorithm, lead V1 was most specific for predicting the foci and the main parameters included: positive/negative P wave in lead V1 indicated CT origin; negative P wave indicated TA or RAA origin; negative/positive and isoelectric/positive indicated CS ostium, superior MA, or left septal origin; isoelectric P wave indicated right septal or perinodal origin; and positive P wave indicated PV, CT, or LAA origin. When this algorithm was used to predict our 61 patients, half of the CS ostium-originated ATs and all the parahisian, superior MA, and one high right septum ATs were predicted wrong. As a result, the algorithm only had an accuracy of 70% in our data. It may be because they used one or two leads to locate the origins of right septum, right pulmonary vein, MA, and CS ostium, with a heavy bias to lead V1, whereas in our patient group, lead V1 was not the same specific. Therefore, in our study, we evaluated the combination of several leads to locate a particular focus of the tachycardia based on the detailed analysis of atrial vector and anatomical locations.

The LA is located to the rear of the chest just in front of the thoracic vertebrae, and the RA is
Figure 4. P-wave algorithm for atrial tachycardia localization. The figure shows the P-wave algorithm developed by detailed analysis of P-wave morphologies in 61 focal atrial tachycardias localized prospectively the site of origin with an accuracy of 90%.

**Narrow P wave with characteristic features not shown in the algorithm suggested localization to a parahisian origin, or other uncommon sites, such as left septum, mitral annulus, and inferior PVs.**

#At least one lead in lead I or aVL is negative.

$Superior MA could be discriminated by low amplitude P waves in limb leads and negative-positive in precordial leads.

**Also could indicate superior TA or right superior septum origin.**

##Close to CS ostium, lower CT-originated AT showed a nonpositive P wave in lead aVR and positive P waves in most of the precordial leads.

Pos = positive, neg = negative.

anterior and slightly right to the LA. The precise anatomical relationship between the atria cannot be assumed and prediction with a single lead therefore cannot achieve good accuracy. Our study showed that the combination of inferior leads with lead aVR and reclassification of sites of origin would create a greater predictive value. P-wave polarity of inferior leads reflects the upper or lower origin of the atrial activation, and lead aVR represents the left or right origin, particularly in the RA. In our new algorithm, anatomical locations of the two defined cardiac areas are consistent with the vector described above. In either reclassified area, it was much easier to localize the particular focus by analyzing the P-wave feature of precordial leads. Precordial leads reflect the projection of vector on the transverse plane. The vector of lead V1 to V6 has the same starting point, so surface P waves in precordial leads could feature polarity migration that may help predict the particular site of tachycardia origin.\textsuperscript{2,5,12,13}

The P-wave feature of CT-originated AT is already well described and therefore its localization from the ECG is not controversial.\textsuperscript{1,10,14} The P-wave feature of AT arising from superior TA was similar to that from RAA and these two were difficult to differentiate from the ECG.\textsuperscript{12,13} As for the right inferior plumonary vein, it was very rare and the P-wave feature was similar to the RSPV and they were always difficult to differentiate.\textsuperscript{5,9}

As a result, the limited data relating to these foci did not influence the accuracy of the algorithm.

The P waves of some uncommon locations may exhibit similar features to more nearby typical foci. We observed one superior fossa ovalis-originated AT with narrower P waves in most of the 12 leads, which was similar to features of an anteroseptal AT. Also, in this case, P waves across the precordial leads migrated from negative to positive in a manner exhibited in AT of RAA origin. Thus, although typical PWMs can predict anatomic locations with fair accuracy, there is still overlap between morphologies because of the closed anatomic locations. These closed locations include the CT and RSPV, the RAA and superior TA, the CS ostium and inferior TA, as well as the LAA and LSPV. Analyzing PWMs of 12-lead ECG is therefore only the first step to distinguish the particular focus of the tachycardia, and revealing the secret of the site of origin still requires electrophysiological study.

**Limitations**

The results of our study cannot be applied to AT patients with enlarged atria or impaired cardiac function and other uncommon sites of focal AT, such as left atrial septum, vena cava, etc. Also, the prospective application and the accuracy of this new algorithm have only been tested on 30 patients, and therefore require more extensive validation.

**Conclusions**

The combination of data from multiple leads and regrouping of sites of origin improve the predictive value for the prediction of atrial tachycarida foci. This study reports a new algorithm that has been developed to predict the origin of focal AT with an accuracy of 90%.

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References


