

ECG Criteria for Localizing the Pulmonary Vein Origin of Spontaneous Atrial Premature Complexes: Validation Using Intracardiac Recordings

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RAJAWAT, Y.S., ET AL.: ECG Criteria for Localizing the Pulmonary Vein Origin of Spontaneous Atrial Premature Complexes: Validation Using Intracardiac Recordings. *We have shown that pacemapping from each of the pulmonary veins reveals unique surface ECG characteristics. However, application of these criteria to spontaneous atrial premature complexes is often difficult because of obscuration by the prior T wave. We hypothesized that the pulmonary vein of origin of spontaneous atrial premature complexes can be determined by measuring characteristics of the P wave whether or not the P wave was superimposed on the prior T wave. We analyzed 58 spontaneous atrial premature complexes of known pulmonary vein origin in 30 patients referred for atrial fibrillation ablation. The origin of all the atrial premature complexes was documented by detailed, intracardiac multipolar catheter mapping. Based on previous work, the criteria for distinguishing right-sided from left-sided pulmonary vein origin of atrial premature complex includes: (1) P wave duration < 120 ms; (2) P wave amplitude in lead I > 0.05 mV; and (3) P wave amplitude in leads II/III > 1.25. The criteria to separate superior from inferior pulmonary veins included the sum of the P wave amplitude in all the inferior leads greater than 0.3 mV. The combination of the P wave duration < 120 ms and the ratio of the P wave amplitude in leads II/III > 1.25, distinguished right-sided from left-sided pulmonary vein origin of spontaneous atrial premature complexes with a sensitivity of 82% and specificity of 100%. The sum of the P wave amplitude in leads II, III, and aVF > 0.3mV distinguished superior from inferior pulmonary vein of origin with a sensitivity of 39% and specificity of 73%. The pulmonary vein origin of spontaneous atrial premature complexes can often be localized using careful quantitative analysis of the surface ECG despite superimposition of the P wave upon the T wave. Separation of right-sided from left-sided pulmonary vein origin of spontaneous atrial premature complexes can be determined with good specificity and sensitivity, while the ability to distinguish inferior from superior pulmonary vein origin is limited. (PACE 2004; 27:182-188)*

atrial fibrillation, radiofrequency catheter ablation, pulmonary vein, atrial premature complex, surface ECG

Introduction

Spontaneous atrial premature complexes (APCs) originating from pulmonary veins (PVs) commonly initiate atrial fibrillation (AF).¹⁻⁵ Our group and others have documented that pacemapping from each of the PVs reveals unique surface ECG characteristics.⁶⁻⁸ It would follow that the surface ECG characteristics of spontaneous APCs might help to localize the PV of origin for these triggers and guide either focal ablation or selective PV isolation. However, application of ECG criteria based on pacemapping to spontaneous APCs may be difficult because of obscuration of the P wave morphology by the prior T wave. The purpose of

this study was to systematically apply ECG criteria to spontaneously occurring APCs documented to originate from the PVs at the time of catheter ablation, and to determine the value of these criteria for localization when applied to spontaneous events. We hypothesized that the criteria developed from PV pacemapping would be able to distinguish right from left, and superior from inferior PV origin of ectopic beats whether or not there was superimposition of the P wave on the prior T wave.

Methods

Patients and Catheters

All procedures were performed after obtaining informed, written consent and followed the institutional guidelines of the University of Pennsylvania Health System. Antiarrhythmic drugs, except amiodarone, were discontinued for at least five half-lives prior to the study. A decapolar catheter with 2-mm electrode spacing (Boston Scientific, EP Technologies, Natick, MA, USA) was

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placed in the coronary sinus (CS) with the proximal electrode pair at the CS os. A second decapolar catheter (Boston Scientific, EP Technologies) was positioned in the posteromedial right atrium along the crista terminalis (CT), with the most distal electrode pair (CT1) in the superior vena cava. Two transeptal punctures were performed using a long introducer sheath (USCI Mullins) under the guidance of fluoroscopy, intracardiac echocardiography (Accuson, Mountain View, CA, USA), and pressure monitoring to access the left atrium. A circular, decapolar mapping catheter with 1-mm electrode spacing (Lasso, Biosense Webster, Diamond Bar, CA, USA) and a Navistar roving ablation catheter (Biosense Webster) were then placed at the os of each PV for recording and mapping. The location of each PV was confirmed by biplane fluoroscopy, intracardiac echocardiography, and magnetic electroanatomic mapping. Patients who did not have four distinct PVs by electroanatomic mapping were excluded.

At the beginning of the procedure, pacing was performed at the os of each PV at threshold from the roving ablation catheter to produce a pacemap template based on the multipolar electrode recordings against which the morphology of spontaneous APCs could be matched.⁹ A programmed digital stimulator (Bloom Electrophysiology, Fischer Imaging Corporation, Denver, Colorado, USA) was used to deliver electrical impulses at approximately twice diastolic threshold. Spontaneous APCs and AF initiations were recorded at baseline with catheters in a right and left PV. If no spontaneous AF initiations occurred, isoproterenol was infused (up to 20 $\mu\text{g}/\text{min}$) to provoke APCs. Surface and intracardiac signals were continuously recorded throughout the study, and spontaneous ectopic P waves were chosen for analysis.

Electrogram Recordings and Measurements

Either spontaneous or provoked APCs were reviewed. In order to avoid any potential bias, only the first APC or AF initiation from any particular PV was chosen for analysis. Signals that were noisy or poor quality were excluded. Intracardiac electrograms were recorded and displayed simultaneously with twelve surface ECG leads on a multichannel EP recording system (Cardiolab, Inc., Houston, TX, USA) at a paper speed of 100 mm/s. The surface ECG signals were sampled at 1000 Hz per channel and filtered from 0.05 to 100 Hz. Bipolar intracardiac electrograms were also sampled at 1000 Hz and filtered between 30 to 500 Hz.

Pulmonary Vein of Origin

The PV of origin was determined using direct recordings of the local PV electrogram from the Lasso or roving ablation catheter. Only when local

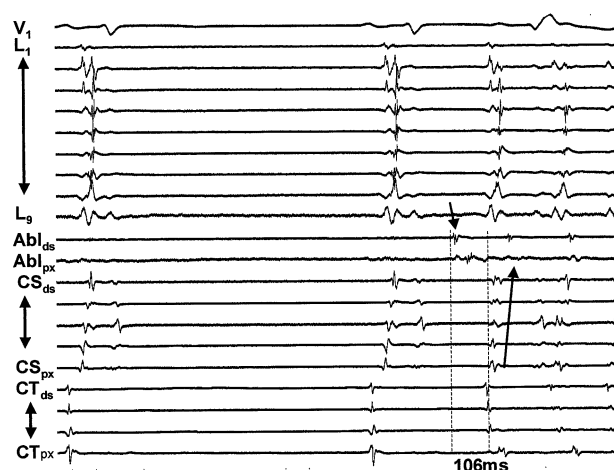


Figure 1. Defining the pulmonary vein of origin. Shown from top to bottom are: ECG lead V_1 , bipolar electrograms from the Lasso catheter in the left superior pulmonary vein (L1 to L9), electrograms from the distal and proximal bipoles of the ablation catheter in the right superior pulmonary vein (RSPV), bipolar electrograms from the coronary sinus catheter (distal to proximal) and bipolar electrograms from the right atrial catheter positioned along the crista terminalis (distal to proximal). The earliest depolarization (small arrow) on the electrogram from the distal bipole of the ablation catheter in the RSPV precedes the earliest coronary sinus (CS) activation by 98 ms. The pattern of activation is typical for an atrial ectopic complex arising from the RSPV, with proximal to distal activation of the CS (long arrow), which is preceded by the crista terminalis recordings. Abl_{ds} = ablation catheter distal end; Abl_{px} = ablation catheter proximal end; CS_{ds} = crista terminalis catheter distal end; CT_{px} = crista terminalis catheter proximal end; LSPV = left superior pulmonary vein; RSPV = right superior pulmonary vein.

PV activation preceded atrial activation in the CS or CT by at least 60 ms and matched the paced template, was origin from a particular PV confirmed (Fig. 1).

Analysis of P Wave Morphology

Based on our previous work using PV pacemapping, the criteria for distinguishing right-sided from left-sided PV origin included: (1) P wave duration < 120 ms; (2) P wave amplitude in lead I > 0.05 mV, and (3) P wave amplitude in leads II/III > 1.25.⁶ The PV origin was more likely to be superior, as opposed to inferior, when the sum of the P wave amplitude in all of the inferior leads is greater than 0.3 mV and more likely to be inferior if there was notching in leads II, III, and aVF. In this study these criteria were applied to spontaneous APCs after the careful assessment

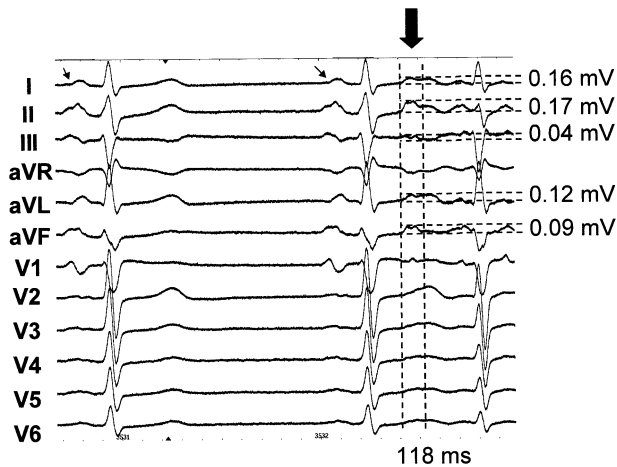


Figure 2. Methods of P wave measurements. Twelve-lead surface ECG recordings showing two sinus beats (small arrow) followed by a spontaneous APC initiating atrial fibrillation buried in the T wave (thick arrow). In this tracing, the onset of the ectopic P wave is best determined by examining leads II and aVF and offset by examining leads III and aVF. The duration of the P wave was measured at 118 ms. The P wave amplitude was measured in individual leads from the onset of the P wave to its peak.

of amplitude and duration of the P wave for these spontaneous events.

The onset and termination of the P wave was determined by carefully examining all 12 leads on the surface ECG displayed at 100 mm/s and comparing the ectopic P wave superimposed on the T wave to a prior unobscured T wave. The duration of the P wave was measured using digital calipers from the onset to the termination of the P wave. The amplitude of the P wave was measured as the difference between the peak amplitude during this interval and the amplitude measured at the onset of the P wave. The presence or absence of P wave notching was determined by visual inspection (Fig. 2).

Statistical Analysis

All values are expressed as the mean \pm standard deviation. Statistical analysis was done using the Student *t*-test (paired or unpaired) or chi-square analysis as appropriate. A *P* value $<$ 0.05 was considered significant. One blinded observer initially performed careful measurement of APC amplitude, duration, and notching without prior knowledge of the PV of origin. A second blinded observer also measured these characteristics for comparison, and differences in APC origin based on these measurements were resolved by consensus.

Results

Pulmonary Vein of Origin

The study group included 30 patients (20 men and 10 women, mean age 55 ± 25 years) with frequent, drug refractory, symptomatic episodes of paroxysmal AF who were referred for ablation of AF triggers. Based on intracardiac electrogram recordings, 19 APCs originated from the right superior PV, 18 from the left superior PV, 17 from the left inferior PV, and 4 from the right inferior PV. Fifteen of the 58 APCs initiated AF, and the remainders reproducibly initiated single APCs.

P Wave Measurements

P waves could be identified and measured in 58 of 62 studied APCs. The remaining 4 (6.5%) APCs, despite careful examination of all 12 surface leads, could not be accurately defined. This may have occurred either because of simultaneous occurrence with the terminal QRS or because the timing with T wave inscription did not allow determining the P wave onset. The majority of these premature complexes, 41 (71%) of 58, were superimposed on the prior T wave and the remainder 17 (29%) of 58, were distinct from the T wave.

Amplitude of P Wave

Amplitudes in the limb leads for spontaneous P waves are shown in Figure 2. The mean amplitude of ectopic P waves in lead I was 0.09 ± 0.03 mV for right-sided PVs and 0.03 ± 0.04 mV for left-sided PVs ($P < 0.01$). The P wave amplitude in lead II was 0.11 ± 0.04 mV for right sided PVs and 0.09 ± 0.04 mV for left sided PVs ($P < 0.05$). The P wave amplitude in lead III of right-sided PVs was smaller than that of left-sided PVs (0.06 ± 0.04 mV vs 0.09 ± 0.04 mV, $P < 0.05$).

A P wave amplitude in lead I $>$ 0.05 mV distinguished right-sided from left-sided PVs with a sensitivity of 78% and a specificity of 86%. A P wave amplitude ratio in leads II/III $>$ 1.25 was 96% sensitive and 70% specific for localizing a spontaneous APC to a right-sided PV origin (Tables I, II, and Fig. 3). A positive ectopic P wave in lead aVL was present in 87% of right PV APCs and 46% of left PV APCs, yielding a sensitivity of 87% and specificity of 54% for separating right-sided from left-sided PV's.

The mean amplitudes for superior PVs in leads II, III, and aVF were 0.1 ± 0.05 mV, 0.09 ± 0.04 mV, and 0.09 ± 0.03 mV and for inferior PVs 0.08 ± 0.05 mV, 0.06 ± 0.03 mV, and 0.07 ± 0.04 mV, respectively ($P = \text{NS}$). When comparing the sum of the P wave amplitudes in leads II, III, and aVF of APCs originating from superior PVs (0.25 ± 0.12 mV), compared to those originating from inferior PVs (0.20 ± 0.10 mV), there was no

Table I.
Ectopic P Wave Characteristics for Right-Sided (n = 23) Versus Left-Sided (n = 35)
Pulmonary Vein of Origin

	P Wave Duration ms	Amp lead I mV	Amp lead II mV	Amp lead III mV	Amp lead aVL mV
RPV	114 ± 9	0.09 ± 0.04	0.11 ± 0.04	0.06 ± 0.04	0.04 ± 0.03
LPV	141 ± 13	0.03 ± 0.04	0.09 ± 0.04	0.09 ± 0.04	0.02 ± 0.03
P	< 0.01	< 0.01	< 0.05	< 0.01	< 0.05

Amp = Amplitude; LPV = Left pulmonary vein; RPV = Right pulmonary vein.

statistically significant difference between amplitude in the upper versus lower PVs (P = 0.12). A cutoff for the sum of the P wave amplitudes in the inferior leads of greater than 0.3 mV had a specificity of 73% and a sensitivity of 39% for distinguishing APCs that originated from superior PVs as compared to those that originated from inferior PVs (Table III, Fig. 4).

Duration of P Wave

There was a significant difference in the P wave duration between right-sided and left-sided PVs. The P wave duration was significantly shorter for right-sided compared to left-sided PVs (114 ± 9 ms vs 141 ± 13 ms; P < 0.001). A P wave duration less than 120 ms was 83% sensitive and 94% specific for differentiating a right-sided from a left-sided PV origin of the APCs.

Notching of P Wave

None of the spontaneous APCs that arose from a right-sided PV had notching of the P wave in lead V₁, while notching was present in 20% of the P waves from APCs that arose from left-sided PVs. Absence of notching in lead V₁ was 100% sensitive but only 20% specific for identifying a right-sided

PV origin of the APCs. Notching in leads II, III and aVF was not statistically significant for differentiating superior versus inferior PV origin for the spontaneous APCs.

Combined Criteria

The best sensitivity and specificity were achieved by combining the following criteria: (1) P wave duration < 120 ms and (2) amplitude in lead II/III > 1.25. This was present in 83% of APCs from right-sided PVs and none of the left-sided PVs, yielding a sensitivity of 83% and specificity of 100% for separating right from left PV origin of spontaneous APCs. The criteria of P wave duration < 120 ms and amplitude in lead I > 0.05 mV was 70% sensitive and 100% specific for distinguishing right-sided PVs from left-sided PVs.

Interobserver Variability

The mean difference between the two blinded observer’s measurements was 3.3 ms for P wave duration and 0.01 mV for P wave amplitude. As for the morphology of P wave, there was 100% interobserver agreement in determining notching of the P wave. The independent measurements of the two observers yielded 86% agreement in the PV of origin based on the above criteria (e.g. amplitude

Table II.
Ectopic P Wave Criteria for Identifying Right-Sided Versus Left-Sided Pulmonary Vein of Origin

	P Wave Duration < 120 ms	Amplitude lead I > 0.05mV	Amplitude lead II/III > 1.25	P Wave Duration < 120 ms & Amp lead II/III > 1.25	P Wave Duration < 120 ms and Amp lead I > 0.05
Sensitivity	83	78	96	83	70
Specificity	94	86	70	100	100
PPV	91	78	69	100	100
NPV	90	86	96	90	83

PV = Pulmonary vein; PPV = Positive predictive value; NPV = Negative predictive value.

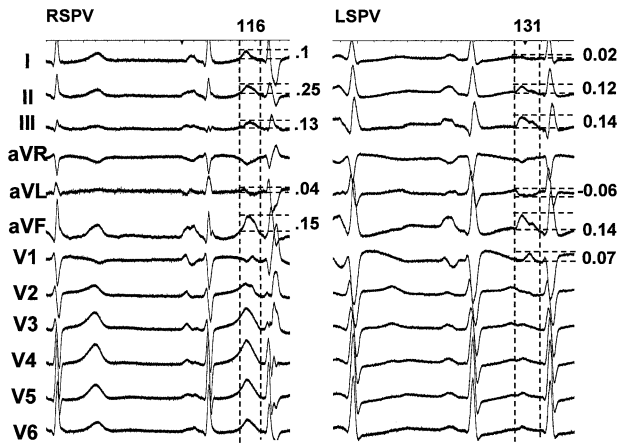


Figure 3. Surface ECG criteria for distinguishing right-sided from left-sided pulmonary vein origin of spontaneous APCs. The left-hand panel shows the 12-lead surface ECG of a spontaneous APC originating from the RSPV while the right-hand panel shows the surface ECG of a spontaneous APC from the LSPV. The duration of the P wave of an APC from the RSPV (116 ms) is shorter than that of the APC arising from the LSPV (131 ms). The P wave amplitude in lead I (0.1 mV) is greater for the APC arising from the RSPV than of the APC arising from the LSPV (0.02 mV). The amplitude in lead II is greater (0.25 mV) than in lead III (0.13 mV) for the APC arising from the RSPV while the opposite is true for the APC arising from the LSPV. LSPV = left superior pulmonary vein; RSPV = right superior pulmonary vein.

$I > 0.05$; duration > 120 ms; amplitude $II/III > 1.25$). Differences were reviewed and resolved by consensus in 96% of the APCs. The remaining 4% APCs were not included for statistical analysis.

Discussion

This study shows that the origin of spontaneous APCs from right-sided versus left-sided PVs can be determined from the 12-lead surface ECG whether or not there is obscuration by the prior T wave. Spontaneous atrial premature com-

plexes originating from right-sided PVs have positive P waves in lead I that are greater than 0.05 mV. In addition, APCs originating from right-sided PVs have P wave amplitudes that are greater in lead II than in lead III and a P wave duration that is usually less than 120 ms. Conversely, spontaneous APCs arising from left-sided PVs was suggested by a relatively low P wave amplitude in lead I (less than 0.05 mV), with a P wave amplitude ratio in leads II/III < 1.25 and a P wave duration of greater than 120 ms. By combining the criteria of P wave duration < 120 ms and P wave amplitude in lead II/III > 1.25 right-sided versus left-sided PV origin of the spontaneous APCs can be determined with 82% sensitivity and 100% specificity.

Diagnostic accuracy for localizing superior versus inferior PV origin of spontaneous APCs was poor. This may be due to the narrow myocardial isthmus that separates superior and inferior PVs, with the potential for myocardial continuity between adjacent veins, a common orifice or the anatomic variations in the level of PV insertion into the posterior left atrial wall among individuals.¹⁰⁻¹² In addition, superimposition of the P wave on the T wave may limit the ability to determine small amplitude differences.

Previous Studies

Morphological features of ectopic P waves have been reported by others. Tang et al. reported that P wave morphology can be used to discriminate right from left atrial tachycardia, and that leads II, III, and aVF are helpful in providing clues for differentiating superior from inferior foci.¹³ We have reported ECG criteria for identifying annular versus CT site of origin of right atrial tachycardia.¹⁴ Tada et al. reported ECG criteria for identifying the site of origin of focal right atrial tachycardia.¹⁵ These studies focused on distinguishing sites within the right atrium and between right and left atrial origin. These studies analyzed P wave morphology qualitatively when the P wave was distinct from the T wave.

Table III.
Ectopic P Wave Criteria, Superior Versus Inferior Pulmonary Veins

	Amplitude lead II mV	Amplitude lead III mV	Amplitude lead aVF mV	Sum of Inferior leads Amplitude mV	Sum > 0.3 mV%
Superior	0.1 ± 0.05	0.09 ± 0.04	0.09 ± 0.03	0.25 ± 0.11	25
Inferior	0.08 ± 0.05	0.06 ± 0.03	0.07 ± 0.04	0.20 ± 0.10	16
P	NS	NS	NS	0.1	
Sensitivity					39
Specificity					73

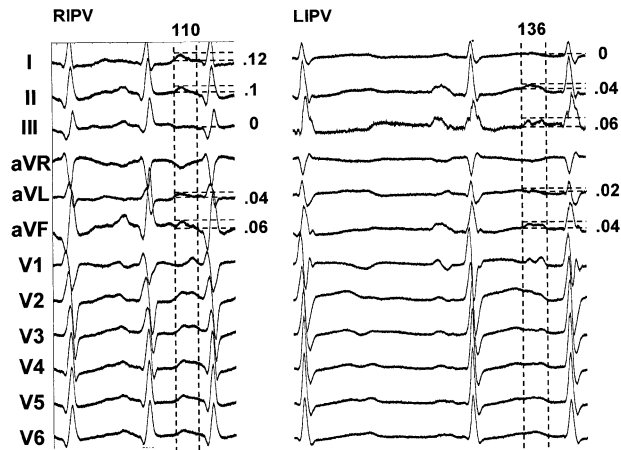


Figure 4. Surface ECG criteria for distinguishing right-sided from left-sided pulmonary vein origin of spontaneous APCs. The left-hand panel shows the 12-lead surface ECG of a spontaneous APC arising from the RIPV while the right-hand panel shows the surface ECG of a spontaneous APC arising from the LIPV. The sum of the P wave amplitudes in inferior leads II, III, and aVF is 0.16 mV for the APC arising from the RIPV while it is 0.14 mV for the APC arising from the LIPV. RIPV = right inferior pulmonary vein; LIPV = left inferior pulmonary vein.

Pacemapping has been evaluated for localizing the origin of APCs from different PVs. However, P wave morphology during pacing may be different from spontaneous ectopic atrial premature complexes, particularly at short coupling intervals. In addition, spontaneous APCs that trigger AF are frequently superimposed upon the prior T wave making analysis difficult.

Tse et al. reported P wave polarity during pacing from PVs and right atrium. They found that the combination of negative or biphasic P wave in lead I and positive P wave in lead V₁ were highly specific for origin from the PVs. A positive P wave in the inferior leads was associated with pacing sites in superior PVs. In this study, the P wave polarity had only limited value in distinguishing pacing sites in left and right pulmonary veins.⁸

Yamane et al. reported P wave characteristics during pulmonary vein pacing. The study showed that right PV pacing produced positive P wave in lead I, flat P wave in lead aVL, and low amplitude ratio of lead III/II. There was a significant difference in the P wave duration between right and left PV, however the ability to distinguish between right and left PV origin was modest. The P wave amplitude in lead II distinguished superior PV from inferior PV with 74% specificity and 81% sensitivity. A notched P wave in lead II showed 92% specificity in predicting a left PV origin.⁷

Similar to the above study we also found that the P wave amplitude ratio in lead II/lead III > 1.25 distinguishes right from left PV origin. We also found that the P wave duration was useful for distinguishing right from left PV origin. In our study P wave amplitude in lead II did not differentiate superior from inferior PV origin. These differences in spontaneous APC morphology may be because of the superimposed T wave or changes in activation with short coupling interval.

Kuo et al. reported that combination of a biphasic or isoelectric P wave polarity in lead V₁ or a biphasic P wave polarity in lead aVL had moderate sensitivity and specificity in predicting an arrhythmogenic focus of AF from superior vena cava (SVC). In this study they studied spontaneous APCs only from SVC and right superior PV.¹⁶

To our knowledge, this is the first study that attempts to correlate the P wave morphology of spontaneous APCs with the PV of origin. The study results document that surface ECG P wave morphology criteria in leads I, II, III and V₁ can predict the right-sided versus left-sided location of arrhythmogenic PVs before more detailed intracavitary recording and mapping that may help facilitate the ablation procedure.

Clinical Implications

Identification of a specific arrhythmogenic PV can be difficult, particularly in patients with infrequent ectopy or no ectopy during ablation procedure. The establishment of surface ECG criteria for identifying the PV origin of spontaneous atrial ectopy may facilitate rapid localization of arrhythmogenic PVs with a single initiating ectopic beat. The described surface ECG criteria can also be used to predict the arrhythmogenic PV during limited lead monitoring prior to the ablation procedure. These data are of critical importance when consideration is given to performing PV isolation only on veins demonstrated to be associated with PV triggers. Such a selective approach may be appropriate in attempting to reduce the risk of complications associated with ablation of all the PVs such as PV stenosis. On the other hand, the presence of confirmed spontaneous events originating from the left and right PVs prior to the procedure may make one more strongly anticipate the need for isolating all the PVs in the absence of frequent spontaneous events that afford the opportunity of more detailed mapping.

Limitations

Although our findings distinguished the origin of spontaneous APCs from the PVs using the surface ECG, the results depend on excellent signal quality. These measurements were made with

digital calipers at fast sweep speed and amplification. It may be more challenging to reproduce this level of accuracy using the standard 12-lead ECG. Patients in this study had normal hearts, did not have bundle branch block, and did not have pacemakers. These data may not apply to patients with heart disease, repolarization abnormalities due to bundle branch block, or pacemakers. In six percent of APCs, PV of origin could not be accurately defined by morphological characteristics of P waves. QRST subtraction combined with a pacemap catalogue may be more helpful in predicting pulmonary vein origin of these APCs.¹⁷ This study is

a retrospective analysis of spontaneous APCs and needs prospective validation.

Conclusion

Analysis of the surface ECG can provide enough information to often help localize the PV origin of spontaneous APCs despite superimposition upon the T wave. Surface ECG criterion based on amplitude and duration in leads I, II, and III can help to distinguish right-sided from left-sided PV origin of spontaneous APCs with excellent sensitivity and specificity. Distinguishing superior from inferior PV origin of spontaneous APCs is limited.

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