# Development and Validation of an ECG Algorithm for Identifying Accessory Pathway Ablation Site in Wolff-Parkinson-White Syndrome

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**ECG Localization of Accessory AV Pathways.** ***Introduction:*** **Delta wave morphology correlates with the site of ventricular insertion of accessory AV pathways. Because lesions due to radiofrequency (RF) current are small and well defined, it may allow precise localization of accessory pathways. The purpose of this study was to use RF catheter ablation to develop an ECG algorithm to predict accessory pathway location.**

***Methods and Results:*** **An algorithm was developed by correlating a resting 12-lead ECG with the successful RF ablation site in 135 consecutive patients with a single, anterogradely conducting accessory pathway (Retrospective phase). This algorithm was subsequently tested prospectively in 121 consecutive patients (Prospective phase). The ECG findings included the initial 20 msec of the delta wave in leads I, II, aVF, and $V_1$ [classified as positive (+), negative (–), or isoelectric (±)] and the ratio of R and S wave amplitudes in leads III and $V_1$ (classified as $R \geq S$ or $R < S$). When tested prospectively, the ECG algorithm accurately localized the accessory pathway to 1 of 10 sites around the tricuspid and mitral annuli or at subepicardial locations within the venous system of the heart. Overall sensitivity was 90% and specificity was 99%. The algorithm was particularly useful in correctly localizing anteroseptal (sensitivity 75%, specificity 99%), and mid-septal (sensitivity 100%, specificity 98%) accessory pathways as well as pathways requiring ablation from within ventricular venous branches or anomalies of the coronary sinus (sensitivity 100%, specificity 100%).**

***Conclusion:*** **A simple ECG algorithm identifies accessory pathway ablation site in Wolff-Parkinson-White syndrome. A truly negative delta wave in lead II predicts ablation within the coronary venous system.** *(J Cardiovasc Electrophysiol, Vol. 9, pp. 2-12, January 1998)*

*Wolff-Parkinson-White syndrome, accessory pathway, electrocardiogram, radiofrequency catheter ablation*

## Introduction

In patients with Wolff-Parkinson-White syndrome, the morphology of the delta wave during sinus rhythm is dependent upon the location of the ventricular insertion of the accessory pathway, which is the site of initiation of ventricular activation. A number of investigators have correlated ECG patterns or algorithms for deciphering the location of the ventricular insertion of the accessory pathway.[1-22] The purpose of this study was to develop a simple, accurate algorithm to be used in examining the 12-lead ECG during sinus rhythm to identify the location of an accessory pathway based upon the site of radiofrequency (RF) catheter ablation of accessory pathway conduction.

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## Methods

### *Study Population*

The study population consisted of 256 consecutive patients referred for RF catheter ablation of a manifest accessory atrioventricular pathway. Subjects with more than one anterogradely conducting accessory pathway were excluded from the retrospective phase of this study. There were 157 men and 99 women (mean age 32 ± 15 years, range 9 to 78).

### *Study Design*

An algorithm to predict accessory pathway location was developed by correlating the preablation ECG with the successful RF ablation site in 135 consecutive patients with a single anterogradely conducting accessory pathway. The algorithm was then tested prospectively in 121 consecutive patients undergoing RF catheter ablation to assess its accuracy in predicting the successful ablation site. A prediction of the accessory pathway location based on the algorithm was made by one of the investigators (M.S.A.) prior to the electrophysiologic study. The location of the ablation catheter was recorded radiographically in the left anterior oblique projection, at an angle in which the catheter recording the His-bundle potential points directly at the observer, and in the right anterior oblique projection, at an angle in which the catheter recording the His-bundle potential lays parallel to the interatrial septum.

### *Ablation Site Nomenclature*

Accessory pathway locations were divided into three main regions, which were further subdivided and are illustrated in Figure 1A.

(I) *Septal accessory pathways* were subdivided into five regions:

- Anteroseptal tricuspid annulus and right anterior paraseptal (AS/RAPS), which includes accessory pathways located up to 10 mm anterior to the His bundle in which both the accessory pathway and a His potential can be recorded from the same bipolar electrode.
- Mid-septal tricuspid annulus (MSTA), which includes accessory pathways located at the septal section of the tricuspid annulus between the posteroseptal and anteroseptal regions.
- Posteroseptal tricuspid annulus (PSTA), including accessory pathways located near the coronary sinus ostium (CSOs).

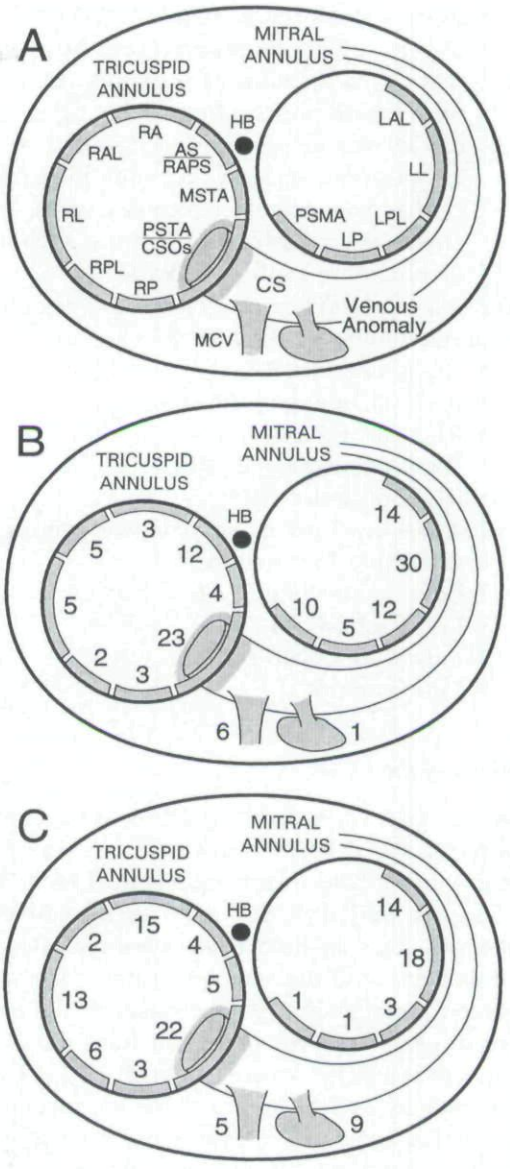


**Figure 1.** *Schematic representation of the heart as viewed in the left anterior oblique projection. (A) Nomenclature used to describe accessory pathway location. RA = right anterior; RAL = right anterolateral; RL = right lateral; RPL = right posterolateral; RP = right posterior; PSTA = posteroseptal tricuspid annulus; CSOs: coronary sinus ostium; MSTA = mid-septal tricuspid annulus; AS = anteroseptal; RAPS = right anterior paraseptal; MCV = middle cardiac vein (coronary vein); CS = coronary sinus; venous anomaly (coronary sinus diverticulum); PSMA = posteroseptal mitral annulus; LP = left posterior; LPL = left posterolateral; LL = left lateral; LAL = left anterolateral; HB = His bundle. (B) Accessory pathway locations (defined by site of successful catheter ablation) in the 135 patients comprising the retrospective group. (C) Accessory pathway locations in the 121 patients comprising the prospective group.*

- Posteroseptal mitral annulus (PSMA).
- Subepicardial posteroseptal accessory pathways, which consist of accessory pathways that required ablation from within the subepicardial venous system (occasionally at the left posterior region), including the middle cardiac vein and other coronary veins; or in anomalies of the coronary sinus, such as a diverticulum (Subepicardial).

(II) *Right free-wall accessory pathways* were subdivided into five regions:
- Right anterior (RA).
- Right anterolateral (RAL).
- Right lateral (RL).
- Right posterolateral (RPL).
- Right posterior (RP).

(III) *Left free-wall accessory pathways* were subdivided into four regions:
- Left anterolateral (LAL).
- Left lateral (LL).
- Left posterolateral (LPL).
- Left posterior (LP).

### *Analysis of the ECG*

A standard 12-lead resting ECG was recorded at a paper speed of 25 mm/sec, at a gain of 10 mm/mV using filter band settings of 0.16 to 100 Hz in each patient 1 day prior to the ablation procedure. The six limb leads were recorded simultaneously and the six pericardial leads were recorded simultaneously. The onset of the delta wave in each lead was measured from the onset of the earliest delta wave in any of the six ECG limb leads as well as in any of the six precordial leads. In the limb leads, the onset of the delta wave was often identified in lead I when it was positive. Otherwise, the earliest delta wave was inscribed in lead aVF.

The polarity of the delta wave was measured within the initial 20 msec of the preexcitation and was classified as positive (+), negative (–), or isoelectric (±), as illustrated in Figure 2A.

## Results

### *ECG Algorithm Development*

The distribution of location of the accessory pathway in the initial 135 patients is illustrated in Figure 1B. ECGs for accessory pathways in each region were examined for distinguishing characteristics. No delta wave characteristics could be identified that reliably differentiated between some contiguous sites, including: RP and RPL; RA and RAL; LP and LPL; and LL and LAL. For this reason, pairs of regions were grouped together in the analysis. An algorithm was devised that correctly identified the accessory pathway location in 117 (87%) of the 135 patients. This algorithm is shown schematically in Figures 3 and 4, and is described below.

*Step 1:* If either the delta wave in lead I is negative or isoelectric or the R wave is greater in amplitude than the S wave in lead $V_1$, a left free-wall accessory pathway is present. If this criterion is fulfilled, lead aVF is examined. If the delta wave in lead aVF is positive, a left lateral/anterolateral (LL/LAL) accessory pathway is identified. If a delta wave in lead aVF is isoelectric or negative, the accessory pathway is located at the left posterior/posterolateral (LP/LPL) region (Figs. 3 and 5).

If the criteria in leads I and $V_1$ are not fulfilled, a septal or right free-wall accessory AV pathway is identified. Proceed to step 2.

*Step 2:* Lead II is examined. A negative delta wave in lead II identifies the subepicardial posteroseptal accessory pathway (Figs. 3 and 6). If the delta wave in lead II is isoelectric or positive, proceed to step 3.

*Step 3:* Lead $V_1$ is examined. A negative or isoelectric delta wave in lead $V_1$ identifies a septal accessory pathway. If this criterion is fulfilled, lead aVF is examined. If the delta wave in lead aVF

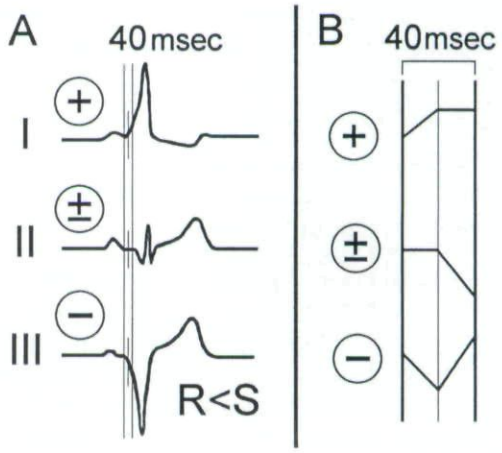


**Figure 2.** *Delta wave polarity was determined by examining the initial 20 msec after earliest delta wave onset in the limb leads as well as precordial leads. (A) ECG leads I, II, and III of a patient with an accessory pathway located at the posteroseptal tricuspid annulus region. Note that it is possible to determine delta wave polarity in all three leads at approximately 20 msec after the onset of delta wave. (B) Determination of delta wave polarity (using the initial 20 msec) in the event of changes within 40 msec.*

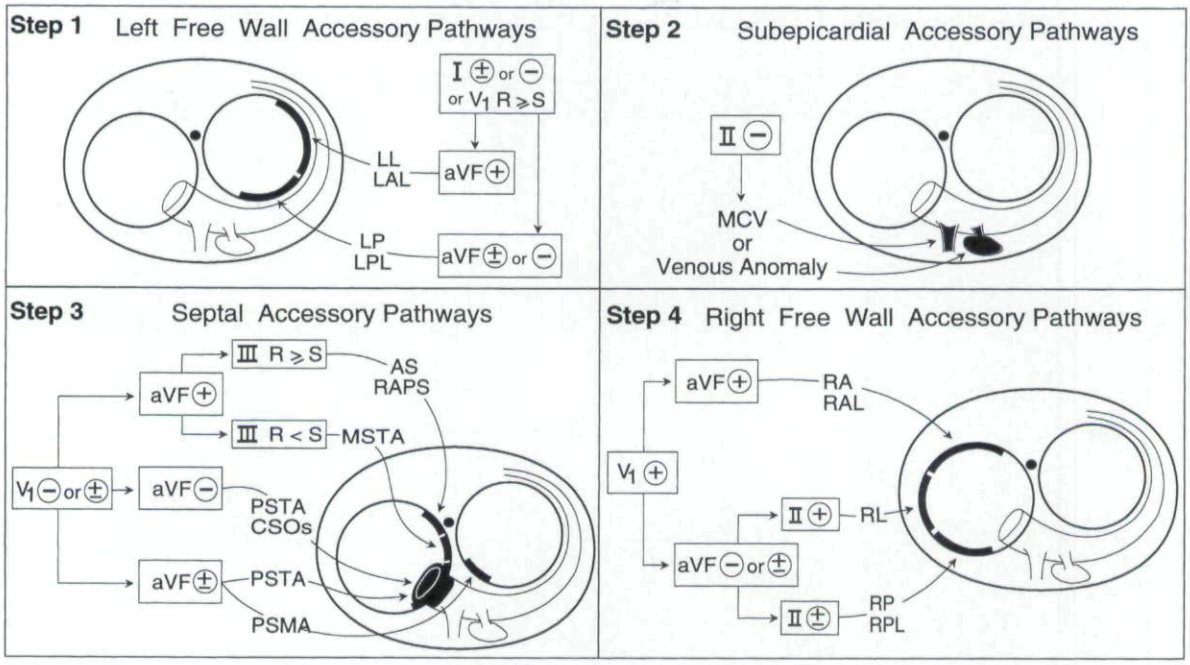


**Figure 3.** *Stepwise ECG algorithm for predicting accessory pathway location. Abbreviations as in Figure 1. See text for explanation.*

is negative, an accessory pathway is identified, which is located at the posteroseptal tricuspid annulus or at the coronary sinus ostium and surrounding region (PSTA/CSOs). If the delta wave is isoelectric in lead aVF, the accessory pathway may be located close to either the posteroseptal tricuspid annulus (PSTA) or the posteroseptal mitral annulus (PSMA) as shown in Figures 3 and 7.

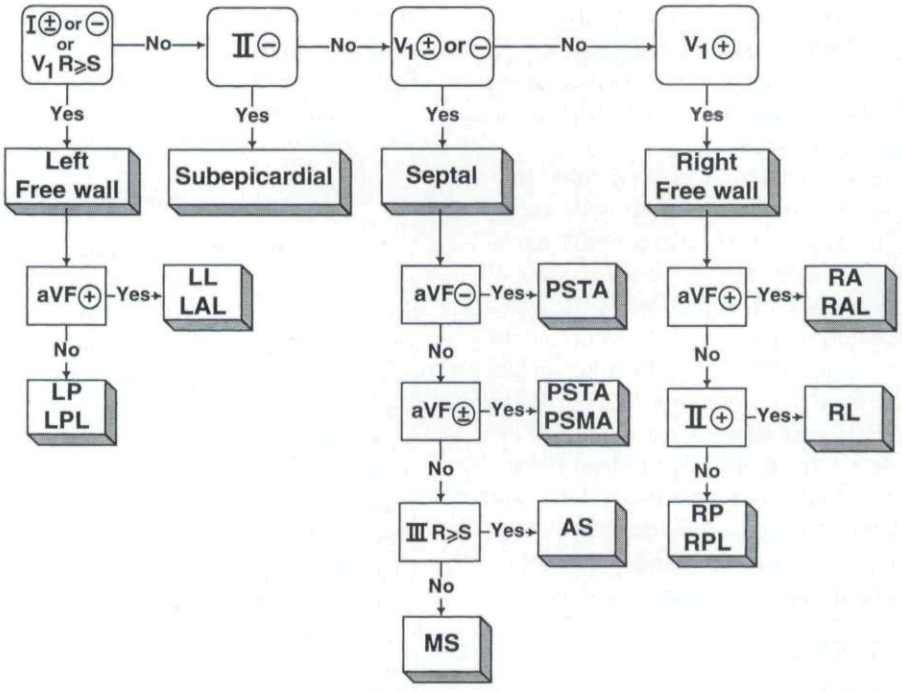


**Figure 4.** *Stepwise ECG algorithm for determination of accessory pathway location. Abbreviations as in Figure 1.*

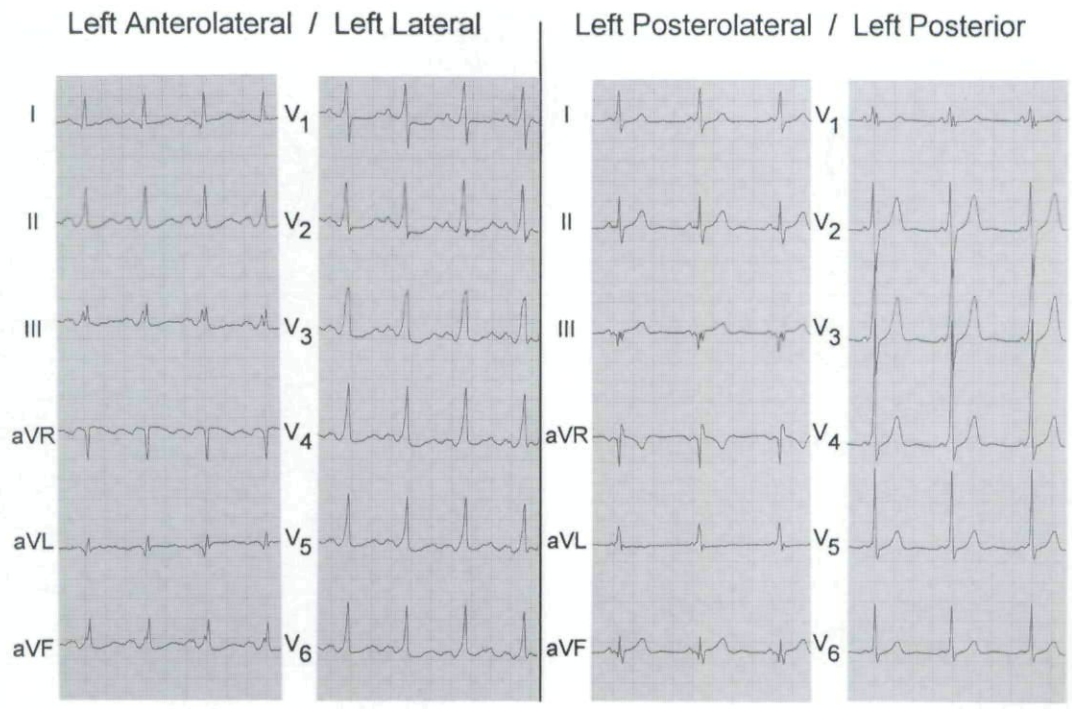


**Figure 5.** *Representative ECG from subjects with a left free-wall accessory pathway. These patients are identified by a (–) or (±) delta wave in lead I, or R ≥ S in lead $V_1$. Delta wave polarity in lead aVF sublocates these accessory pathways.*

A positive delta wave in aVF identifies a pathway located within the anteroseptal/right anterior paraseptal (AS/RAPS) or mid-septal tricuspid annulus (MS) regions. These two regions are differentiated by examining the R/S ratio in lead III: R ≥ S identifies anteroseptal/right anterior paraseptal (AS/RAPS) accessory pathway, and R < S identifies an accessory pathway located along the mid-septal tricuspid annulus (MSTA), as illustrated in Figures 3 and 8.

If the delta wave in lead $V_1$ is positive (after having excluded patients with a left free-wall accessory pathway in Step 1), a right free-wall accessory AV pathway is identified. Proceed to step 4.

*Step 4:* In patients with right free-wall accessory pathways, examine lead aVF. A positive delta wave in lead aVF identifies a right anterior/anterolateral accessory pathway (RA/RAL). If the delta wave in aVF is isoelectric or negative, examine lead II. A positive delta wave in lead II identifies a right lateral accessory pathway (RL), and an isoelectric delta wave in lead II identifies a right posterior/posterolateral accessory pathway (RP/RPL), as illustrated in Figures 3 and 9.

### *ECG Algorithm Validation*

The ECG algorithm was then tested prospectively in 121 consecutive patients. The distribution of accessory pathway location based upon site of successful ablation is shown in Figure 1C. The relationship between the predicted location (based upon the ECG algorithm) and the actual location (based upon ablation site) is shown in Table 1. The algorithm correctly identified accessory pathway locations in 109 patients (sensitivity 90%, specificity 99%, positive predictive value 93%, and negative predictive value 98%), calculated as weighted averages (weighted by number of true positives).

## Discussion

Several attempts have been made to correlate electrocardiographic findings with anatomic locations of accessory AV pathways in patients with Wolff-Parkinson-White syndrome.[1-22] ECG criteria based upon surgical dissection of accessory pathways have shown accuracy in identifying accessory pathway location.[2-12] The ECG algorithm developed in this study differs from prior algorithms in its combined use of the resting (not during atrial pacing) ECG, utilization of only five ECG leads, localization by catheter ablation techniques (which may allow precise localization of the accessory pathway), and by prospective validation of the algorithm. This algorithm is particularly accurate in predicting ablation at sites near the AV node and His bundle with risk of AV block,

**TABLE 1**
Correlation Between Predicted Accessory Pathway Location (ECG Algorithm) and the Actual Location Based on Ablation Site

| | | Predicted Location | | | | | | | | | | Accuracy | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ablation Site | (n) | RA RAL | RL | RP RPL | AS RAPS | MSTA | PSTA | PSMA | LP LPL | LL LAL | Subepicardial | Sens (%) | Spec (%) | + P Value (%) | − P Value (%) |
| RA/RAL | 17 | 17 | | | | | | | | | | 100 | 97 | 85 | 100 |
| RL | 13 | 1 | 11 | | 1 | | | | | | | 85 | 100 | 100 | 98 |
| RP/RPL | 9 | 1 | | | | | | | | | | 89 | 100 | 100 | 99 |
| AS/RAPS | 4 | 1 | | 8 | 3 | | | | | | | 75 | 99 | 75 | 99 |
| MSTA | 5 | | | | | 5 | | | | | | 100 | 98 | 71 | 100 |
| PSTA | 22 | | | | | 2 | 18 | | 2 | | | 82 | 100 | 100 | 96 |
| PSMA | 1 | | | | | | | 1 | | | | 100 | 99 | 50 | 100 |
| LP/LPL | 4 | | | | | | | 1 | 3 | | | 75 | 96 | 38 | 99 |
| LL/LAL | 32 | | | | | | | | 3 | 29 | | 91 | 100 | 100 | 97 |
| Subepicardial | 14 | | | | | | | | | | 14 | 100 | 100 | 100 | 100 |
| Total | 121 | | | | | | | | | | | 90 | 99 | 93 | 98 |

*Accessory pathway location abbreviations as shown in Figure 1A.
Sens = sensitivity; Spec = specificity.

such as mid-septal and anteroseptal regions, and for predicting ablation of subepicardial accessory pathways from the venous system, such as coronary veins and anomalies of the coronary sinus. This latter region has been associated with failed ablation and cardiac perforation.[23] To facilitate the interpretation of delta wave polarity, this algorithm only uses the initial forces of preexcitation (initial 20 msec) after the earliest delta wave onset in any of the limb leads as well as the precordial leads to characterize delta wave polarity. This may avoid misinterpretation when changes in polarity occur within 40 msec, which is not an uncommon finding (illustrated in Fig. 2B and shown in lead II of Fig. 7, left panel). Also, analysis of only the initial 20 msec of delta wave may help to identify some left free-wall accessory pathways producing minimal preexcitation in sinus rhythm or pathways exhibiting slow anterograde conduction.

### *ECG Criteria Based upon RF Catheter Ablation of Accessory AV Pathways*

RF catheter ablation has been used widely for treating patients with an accessory pathway.[23-27] Certain ECG findings may correlate with the location of accessory pathways in these patients. We have reported previously a preliminary ECG algorithm for identifying posteroseptal accessory pathways[13] and subsequently for identifying accessory pathways located at 10 different sites around the tricuspid and mitral annuli using only ECG leads I, II, aVF, and $V_1$.[14] Others have used the maximally preexcited 12-lead ECG during sinus rhythm or atrial pacing, delta wave polarity in the initial 40 msec of the preexcited QRS complexes, and frontal and horizontal delta wave axis were used for analysis.[16] Combination of multiple variables, such as (1) precordial transition, (2) R and S waves amplitude ratio, (3) sum of the polarities of delta wave, (4) amplitude of delta wave, (5) delta wave axis in the frontal plane, and (6) amplitude of R wave, have been used with success,[17] but the analysis of this complex set of variables is yet to be validated prospectively. In two other studies, the ECG algorithm was tested prospectively. One used the polarity and morphology of QRS complexes and the highest R wave amplitude in the precordial leads.[18] They showed an 86% accuracy in locating accessory pathways at nine sites around the tricuspid and mitral annulus. The specific sensitivities and specificities were not reported and, due to the small number of patients and the fact that a broad region on the right

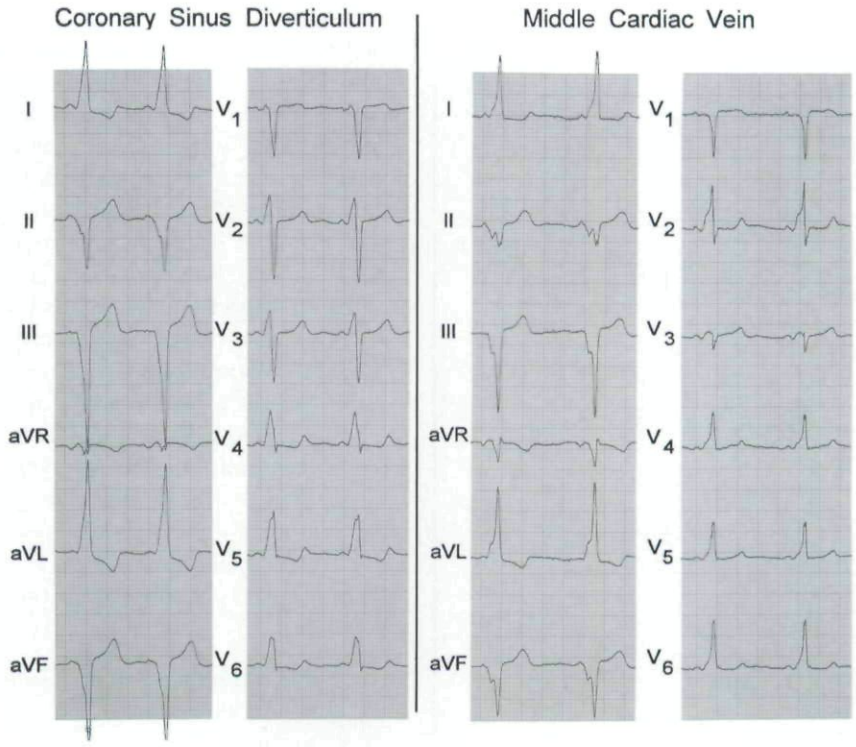


**Figure 6.** *Representative ECG from subjects with a subepicardial accessory pathway. These patients are identified by a (–) delta wave in lead II (after excluding subjects with a left free-wall accessory pathway). Note the typical pattern of the delta wave in lead II: it is negative and joins the end of the P wave.*

free wall had to be combined to a single site may compromise the resolution of their algorithm. The other study in which the ECG algorithm was validated prospectively[19] used a similar design and resolution to our preliminary reported results.[14] Nevertheless, our algorithm exhibited a positive predictive accuracy of 93% in locating accessory pathways at 10 different sites. In addition, we could distinguish anteroseptal from right anterior accessory pathways, whereas their algorithm could not discriminate accessory pathways located in a high-risk region for AV block (anteroseptal) from accessory pathways located in a relatively low-risk region (right anterior).

### *Utility of the Algorithm for Identifying Accessory Pathways Requiring Ablation from the Subepicardial Venous System*

Surgery for Wolff-Parkinson-White syndrome has shown that accessory pathways may be associated with coronary sinus venous anomalies such as aneurysms and diverticula.[28-34] We have reported previously that some accessory pathways require ablation from within the coronary venous system in the subepicardial posteroseptal[35,36] and left free-wall[37] regions. Other investigators have also used RF energy to ablated accessory pathways from the coronary sinus, middle cardiac vein, and coronary sinus diverticulum.[38-40]

Accessory pathways associated with coronary veins and anomalies of the coronary sinus may account for catheter ablation failure at the tricuspid and mitral annulus. In our institution, approximately 40% of patients referred following at least one unsuccessful ablation attempt for a posteroseptal accessory pathway required ablation from coronary veins or anomalies of the coronary sinus.[36] In this study, a negative delta wave in ECG lead II was useful in predicting ablation from coronary veins and anomalies of coronary sinus in all 14 patients. It is important to rule out a brief initial isoelectric segment of the delta wave in lead II before labeling it as negative. This initially isoelectric delta wave may be followed by a negative component that is often associated with an accessory pathway located at the posteroseptal tricuspid annulus, and right posterior and right posterolateral regions (Fig. 2A and Fig. 7, left panel). An ECG exhibiting a true negative delta wave in lead II will also show a negative delta wave in leads III and aVF (Fig. 6). In our experience, this finding is associated with

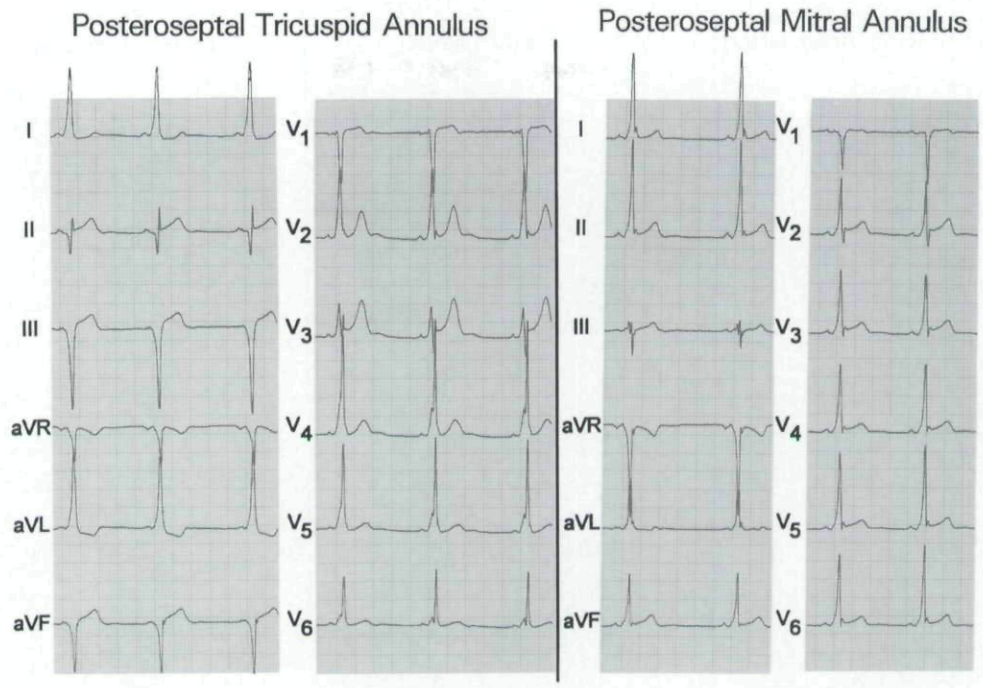


**Figure 7.** *Representative ECG from subjects with a septal accessory pathway. These patients are identified by a (–) or (±) delta wave in lead $V_1$ (after excluding subjects with a left free-wall or subepicardial accessory pathway). Delta wave polarity in lead aVF sublocates these septal accessory pathways. See text for discussion.*

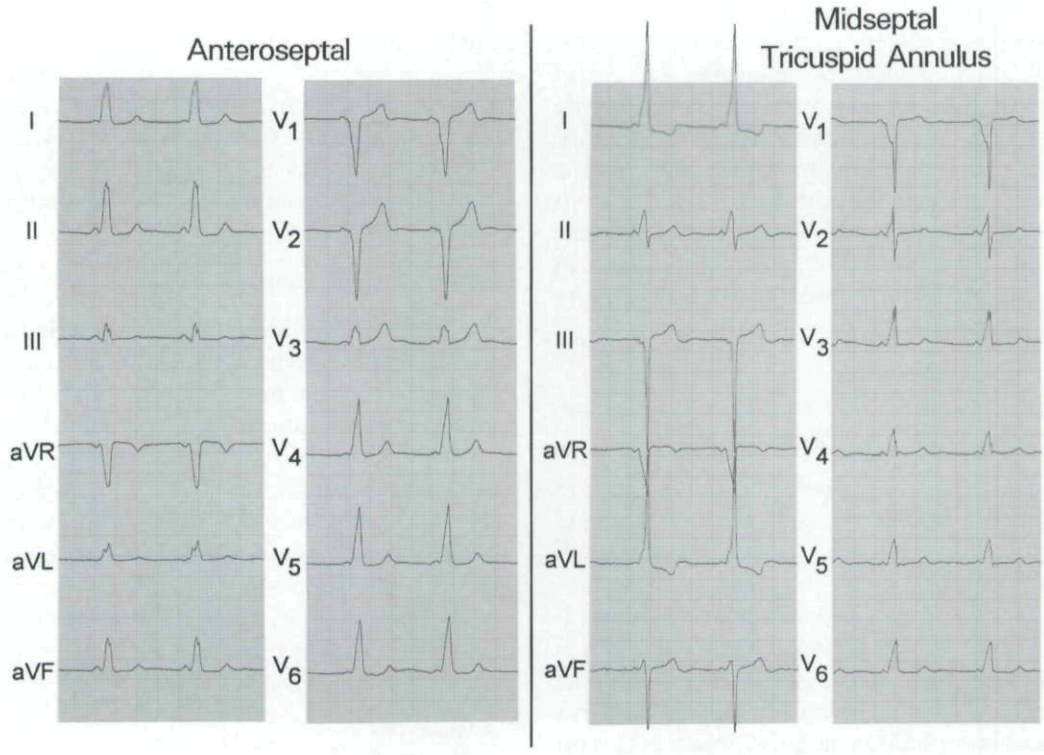


**Figure 8.** *Representative ECG from subjects with a septal accessory pathway. These patients are identified by a (–) or (±) delta wave in lead $V_1$ (after excluding subjects with a left free-wall or subepicardial accessory pathway). A (+) delta wave polarity in lead aVF sublocates these septal accessory pathways at either the midseptal or anteroseptal tricuspid annulus regions. The precise region is determined by the R/S ratio in lead III. See text for discussion.*

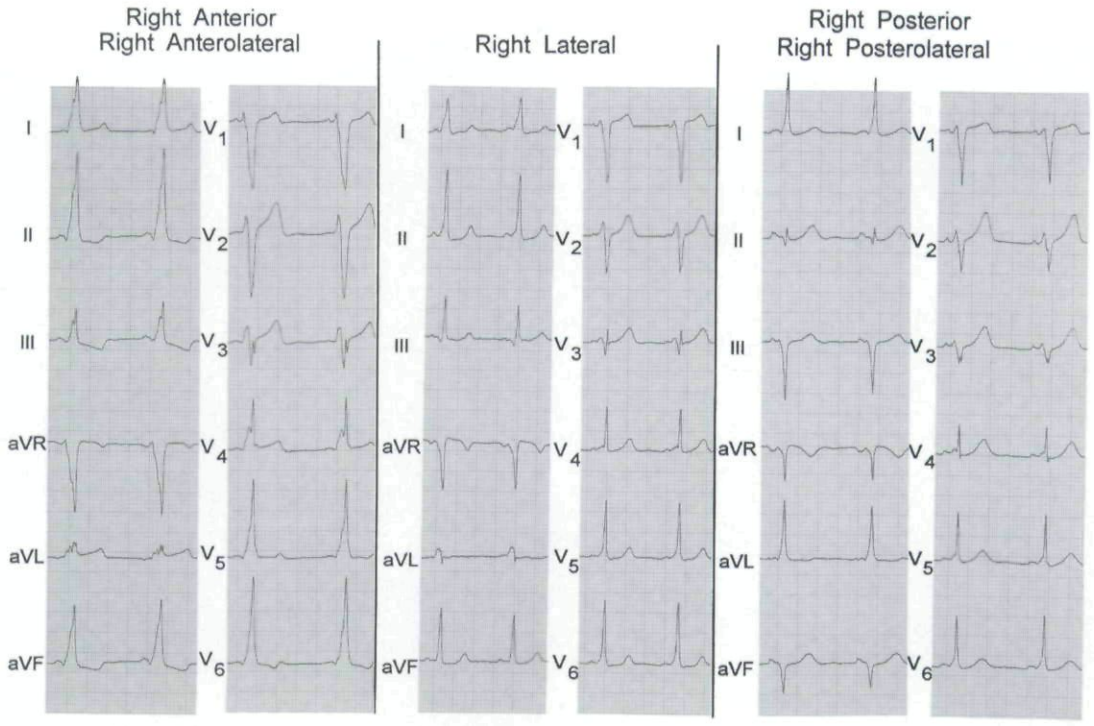


**Figure 9.** *Representative ECG from subjects with a right free-wall accessory pathway. These patients are identified by excluding subjects with a left free-wall, subepicardial, or septal accessory pathway. See text to sublocate these accessory pathways at the free-wall tricuspid annulus.*

a posteroseptal accessory pathway having a subepicardial ventricular insertion, requiring successful ablation from the coronary venous system. Despite the fact that a negative delta wave in the inferior leads is generally accepted to be associated with a posteroseptal accessory pathway, the ECG from patients requiring successful ablation from the endocardium may show a negative delta wave in leads III and aVF, but unlikely a negative delta wave in lead II.

### *Utility of the Algorithm for Identifying Anteroseptal and Mid-Septal Accessory Pathways*

Surgical dissection as well as catheter ablation of accessory pathways located near the AV node and His-bundle region have been associated with procedure failure and AV block.[5,11,26,41] This accounts for a significant proportion of the morbidity of RF ablation procedures.[26] Mid-septal accessory pathways were first described as intermediate septal accessory pathways exhibiting positive delta wave morphology in ECG leads I, II, and aVL, and isoelectric in leads III and aVF.[5,11] In this study, the initial forces of the delta wave in lead aVF were positive (Fig. 8, right panel). Others have separated the mid-septal region into three zones and, in agreement to our findings, a positive delta wave in lead aVF correlated with a mid-septal accessory pathway in close proximity to the AV conduction system.[21] In this study, 3 of 4 anteroseptal and all 5 of 5 mid-septal accessory pathways were correctly localized by the algorithm.

### *Clinical Implications*

As the ECG algorithm accurately localizes accessory pathways prior to ablation, it may help the physician advise the patient regarding the likelihood of success and complications of the procedure, in particular subjects with anteroseptal or mid-septal accessory pathways. The ECG algorithm may aid selection of patients in whom coronary sinus angiography should be performed in order to delineate its anatomy, thus allowing mapping in the coronary veins and anomalous structures of the coronary sinus.

### *Limitations*

Multiple accessory pathways have been documented in 2% to 20% of subjects.[42-44] In the retrospective phase of our study, we only included patients with a single anterogradely conducting ac-

cessory pathway. During the prospective phase, there were no patients with more than one accessory pathway exhibiting anterograde conduction. Because of the limited experience in using this algorithm in subjects with multiple pathways, we cannot comment on its utility in this setting. Accessory AV pathways exhibit a slant course across the mitral or tricuspid annulus, and delta wave morphology is dependent upon the site of ventricular insertion of accessory pathways. This ECG algorithm does not necessarily identify the site of earliest ventricular activation (ventricular insertion). It was developed based upon the site of successful RF catheter ablation of accessory pathways, which were determined primarily by recordings of accessory pathway activation potential. Therefore, the slant course of accessory pathways, which could account for error in localization, should not influence the accuracy of this ECG algorithm. Previous catheter ablation may limit the usefulness of an ECG algorithm. The necrosis of tissue around the ventricular insertion of the accessory pathway may affect the sequence of ventricular preexcitation, accounting for a different delta wave pattern on the ECG. Nevertheless, it did not appear to affect the accuracy in our study, as 48 of 121 patients (40%) had had a previous failed ablation.

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