Testing of a New T-Wave Subtraction Algorithm as an Aid to Localizing Ectopic Atrial Beats

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Background: Identifying the timing and morphology of an ectopic P wave from the surface electrogram can aid in the diagnosis and localization of atrial arrhythmias. Given the relatively short coupling interval of atrial ectopic beats, the P wave is often obscured by the larger amplitude QRS-T wave complex. A method to uncover such "buried" P waves using a standard 12-lead surface ECG would be clinically useful and could potentially be a noninvasive guide to catheter ablation of focal atrial tachycardia.

Methods: We developed an automated computerized program (BARD DUO LAB SYSTEM™) designed to subtract the QRS-T wave complex from the surface electrogram and uncover a previously obscured P wave. The purpose of the present study was to validate this program. The surface ECG from 21 patients undergoing atrial pacing during electrophysiologic study (group I) and 10 patients with atrial tachycardia (group II) were analyzed and the derived P-wave morphology assessed using correlation waveform analysis (CWA) and visual grading by three reviewers.

Results: The algorithm successfully uncovered the P wave in each surface ECG. For the 21 patients in group I, average CWA comparing the derived P wave with the previous paced P wave was 83%. Average CWA for group II was 82%. Visual grading of the match between derived P waves and paced P waves revealed a 21/21 match in group I patients and a 12/12 match in 9/10 of group II patients.

Conclusions: An ectopic atrial P wave obscured by a coincident QRS-T wave complex can be accurately uncovered using this new algorithm. Addition of this technique to existing methods may improve the diagnosis of atrial arrhythmias and aid in the localization and ablation of ectopic atrial foci.

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The timing and morphology of a P wave can be used to help localize its origin within the atria and aid in the diagnosis and treatment of supraventricular arrhythmias.^{1–7} Atrial ectopic beats typically have a short coupling interval leading to simultaneous atrial activation and ventricular repolarization.⁸ Given the relatively smaller mass of myocardium and corresponding lower voltage in the atria compared with the ventricles, the P-wave morphology is commonly obscured by the larger QRS-T wave complex. This is a frequent occurrence limiting the diagnosis of supraventricular tachycardia recorded on 12-lead ECGs, telemetry recordings, and Holter monitor tracings. It is also a limitation

in the electrophysiological laboratory, where the P-wave morphology can help localize ectopic atrial foci and guide catheter ablation of atrial tachycardia and atrial fibrillation but where ectopic atrial beats are often infrequent and obscured by the QRS-T wave complex.^{9,10} A practical method designed to reveal the morphology of a P wave buried within the QRS-T wave complex, would therefore, be useful. SippensGroenewegen et al. recently developed an automatic QRS-T subtraction algorithm to subtract ectopic P waves from the QRS-T complex with body surface mapping using 62-lead ECG recordings.¹¹ We developed an automated computerized t-wave subtraction program using the typical

12-lead ECG recording used in standard electrophysiologic studies and catheter ablation procedures (BARD DUO LAB SYSTEM™). To validate this new t-wave subtraction algorithm, we quantitatively and visually analyzed spontaneous and derived P-wave morphologies obtained from surface ECG recordings of spontaneous atrial ectopy and those generated with endocardial atrial pacing.

METHODS

We retrospectively studied the recorded surface electrocardiographic recordings of premature atrial pacing from 21 consecutive patients who had undergone diagnostic electrophysiologic study and from 10 patients who had undergone radiofrequency (RF) catheter ablation for focal atrial tachycardia to validate this algorithm. Each patient had given informed signed consent and underwent conscious sedation. Six French quadripolar electrode catheters (Bard Electrophysiology, Lowell, MA) were placed at the high right atrium, His bundle, and right ventricular apex using fluoroscopic guidance. For atrial tachycardia patients, a coronary sinus catheter was placed.

Group I

Atrial pacing was delivered at twice the atrial-pacing threshold to ensure consistent capture. Twelve-lead electrocardiographic recordings were obtained during premature stimulation. Premature stimulation was performed in the high right atrium at a drive pacing cycle length long enough to ensure that each paced P wave occurred after the preceding T wave. A single premature extrastimulus was delivered at three progressively decreasing coupling intervals resulting in paced P waves being scanned into different segments of the T wave (Fig. 1). Using an automated computerized program (BARD DUO LAB SYSTEM™), a 12-lead QRS-T wave template was made from the native QRS complex. When possible, the template was taken from the preceding QRS interval to limit the effects of respiratory variation on the QRS-T wave complex. A QRS-T wave complex containing a paced P wave was then selected and the native QRS template subtracted from it (Fig. 1). The derived P wave was compared to the visible paced P wave from the drive train using two methods: correlation waveform analysis (CWA)¹²⁻¹⁹ and visual comparison by two reviewers. CWA calculates

Figure 1. Twelve-lead ECG demonstrating a paced P wave delivered into the peak of a T wave and during the isoelectric period. A P wave derived from t-wave subtraction is then demonstrated along with a comparison of its morphology to the exposed paced P wave using CWA.

correlation coefficients (ρ) based on the degree of match between the rates of rise and fall of the two waveforms, independent of amplitude or unit:

$$\rho = \frac{\sum_{i=1}^N (T_i - \bar{T})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^N (T_i - \bar{T})^2 \sum_{i=1}^N (S_i - \bar{S})^2}}$$

The value of the correlation coefficient is always between -1 and $+1$, where $+1$ denotes a perfect match and a -1 denotes a perfect mismatch (mirror image waveform) between the signal (S) and the template (T). We converted the correlation coefficient into a percentage with 100% representing a perfect match. A percentage is provided for each individual lead as well as the average of all 12 leads for each patient studied. Two reviewers who compared the morphology of the two P-wave complexes performed visual assessment. Each complex was assigned a value of either positive, if the complex was predominantly above the baseline; negative, if the complex was predominantly below the baseline; isoelectric, if neither above nor below the baseline; and biphasic, if both above and below the baseline. The two complexes were considered a match if each P wave was in the same

morphological category. A third blinded reviewer performed visual assessment to settle any disagreements. The average CWA after elimination of all isoelectric leads (assessed visually) was calculated separately.

Group II

Surface electrograms were then analyzed from 10 patients undergoing electrophysiological study for atrial tachycardia or atrial fibrillation with an initiating atrial focus. Each patient had atrial ectopy or atrial tachycardia that spontaneously occurred. To be included for analysis, surface ECGs had to include visible ectopic P waves as well as ectopic P waves obscured by the QRS-T wave complex. Using CWA and visual assessment, visible ectopic P waves were compared with ectopic P waves derived from t-wave subtraction as described above (Fig. 2).

Figure 2. Twelve-lead ECG demonstrating an ectopic atrial beat with its P wave buried in the QRS-T wave complex, the exposed ectopic P wave, and the ectopic P wave derived from t-wave subtraction. CWA comparing the postsubtraction P wave and exposed ectopic P wave is shown.

RESULTS

The t-wave subtraction algorithm successfully uncovered a P wave in each of the tracings for the 21 patients undergoing premature atrial stimulation and in all 10 patients with spontaneous atrial ectopy. For group I patients undergoing extrastimulus pacing, CWA comparing the derived P wave with the previous paced P wave resulted in an average correlation of 83%. The average of the CWA results for the 10 patients with atrial tachycardia was similar at 81%. The poorest correlation appeared to be in the most isoelectric leads, such as leads I, V₄, V₅, and V₆ where the noise-to-P-wave amplitude was the greatest. Three group II patients had left atrial foci with an average correlation of 84%. The remaining seven patients had right atrial foci with an average CWA of 81%. Average CWA after elimination of leads with isoelectric P waves was 89% for group I patients and 91% for group II patients. Visual grading of the match of morphology between derived P waves and paced P waves revealed a 12/12 match in all group I patients and a 12/12 match in 9/10 group II patients with one patient obtaining an 11/12 match.

DISCUSSION

This study demonstrates that the 12-lead ECG can be used successfully to perform t-wave subtraction and unmask the morphology of premature atrial complexes obscured by a larger amplitude QRS-T wave complex. The morphology of the derived P wave matched the native P wave very well with visual inspection and quantitative analysis.

Prior studies by SippenGroenwegen et al. have shown that a body surface integral map may be used to unmask the P wave buried in a T wave.¹¹ We demonstrate that t-wave subtraction can be performed using standard 12-lead ECG equipment, which is a more readily available tool for guiding arrhythmia localization and catheter ablation. The QRS-T wave template used in the study by SippenGroenwegen was derived from an average of multiple beats in normal sinus rhythm or during atrial overdrive pacing. This technique was hindered by the development of varying degrees of rate-related ventricular aberrancy that intermittently developed at faster heart rates. In our algorithm an individual beat may be used as a template.

In this era of successful treatment of atrial tachycardia and focally initiated atrial fibrillation using

RF catheter ablation, accurate and efficient localization of ectopic atrial foci is critical.^{8,20-24} Despite the advent of more sophisticated mapping systems and more advanced imaging modalities, localization of atrial arrhythmias can be technically challenging and time consuming. A noninvasive guide to atrial arrhythmia localization could facilitate catheter ablation by focusing the mapping process to a particular location within the atria, allowing better planning of procedure time with reduced fluoroscopy use, and by allowing identification of two or more distinct initiating foci. Identifying the P-wave morphology could also allow the use of more traditional pacing techniques such as pace mapping.

Although atrial anatomy is complex and variable from patient to patient, several groups have demonstrated the ability to use surface ECG criteria and intracardiac electrograms from the atria to suggest a site of origin of atrial arrhythmias. Using a canine model, Sir Thomas Lewis demonstrated as early as 1910 that pacing different regions of the atrium resulted in distinct P-wave morphologies.²⁵ Several subsequent studies demonstrated characteristic P-wave morphologies with foci originating in the left atrium. Mirowski et al. found that a "dome and dart" configuration of the P wave in the precordial leads was typical of left atrial activation in normal hearts.²⁶ Studies of P-wave morphology in animals and humans went on to describe additional ECG criteria suggestive of initiation of electrical activation from the left atrium. These include the following: (1) frontal plane mean P-wave axis from +106 to +270°, (2) negative P waves in leads I and V₆, and (3) biphasic or isoelectric P wave in lead V₁.²⁶⁻²⁹ Tang et al. showed that P-wave morphology could distinguish the left- from the right-sided sites of origin with a sensitivity of 88-93% and a specificity of 79-88% depending on the criteria used.³ Gelb et al. went on to show that P-wave morphology could distinguish between foci within the right atrium.³⁰ Using intracardiac atrial electrograms, Saba et al. demonstrated that CWA could distinguish retrograde atrial activity from normal sinus rhythm.¹⁹ SippensGroenewegen et al. used an atlas of paced P-wave integral maps to localize the site of origin of right atrial arrhythmias.³¹ It is quite possible that a more extensive database of surface P-wave morphologies may allow more accurate localization of ectopic sites including the pulmonary veins and superior vena cava.

Pace mapping may be used to localize ectopic atrial rhythms. Man et al. used unipolar pacing in the coronary sinus and right atrium to show that the spatial resolution of atrial pace mapping is approximately 17 mm.³² Saba et al. demonstrated that sites as close as 5 mm could be distinguished using CWA of surface electrogram morphology.³³ Weiss et al. successfully ablated ectopic atrial rhythms in eight patients using a perfect match of P-wave morphology³⁴ and Pappone et al. found that atrial pace mapping and an AP interval greater than or equal to 30 ms were reliable features to predict the outcome of the ablation procedure in 59 patients.³⁵

STUDY LIMITATION

The present study was not designed to compare the accuracy of this algorithm at different locations. Three of our group II patients had a left-sided origin of atrial tachycardia confirmed with mapping and ablation, whereas the other patients had right atrial sites.

Whereas the use of CWA to quantitatively determine the degree of morphological match has been validated, it is unclear what percentage match constitutes an acceptable level to allow accurate visual assessment.¹²⁻¹⁹ Furthermore, the use of CWA to examine leads with low-voltage P waves appeared to be limited in this study. This is likely due to a higher noise-to-voltage ratio leading to a lower percentage match in these leads. We feel that visual assessment is a more clinically useful method of validating such an algorithm and we have included CWA and visual assessment so as to have a quantitative and qualitative evaluation of the algorithm.

CONCLUSION

By uncovering ectopic P-wave morphology buried within the QRS-T wave complex, this new real-time 12-lead ECG algorithm may be a practical noninvasive guide to the diagnosis and localization of supraventricular arrhythmias. Future studies of atrial pace mapping using this technique and the development of more extensive libraries of atrial P-wave morphologies will likely further enhance its utility.

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