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Original Article

Pace mapping in the atrium using bipolar electrograms from widely spaced electrodes

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ABSTRACT

Background: Pace mapping is a useful tool but is of limited utility for the atrium because of poor spatial resolution. We investigated the use of bipolar electrograms recorded from widely spaced electrodes in order to improve the resolution of pace mapping.

Methods: This prospective study included patients undergoing a clinical electrophysiology study. Unipolar pacing from either the superior or inferior lateral right atrium was performed to simulate atrial tachycardia. Twelve-lead electrocardiograms were recorded during pacing as a template. In addition, three intracardiac bipolar electrograms from a set of widely spaced electrodes were also recorded. Subsequently, unipolar pacing was performed from electrodes at known distances from the initial pacing site, and the morphology of P waves in the electrocardiogram and bipolar electrograms were compared with that of the template. Morphological comparison was performed by a cardiologist and by automated computerized matching. Spatial resolution was calculated as the minimum distance at which there was no match.

Results: Fifteen patients participated in the study. Distance at which differences in morphology were noted was smaller in the bipolar electrograms compared to that indicated by P waves in the electrocardiogram, when matched by the cardiologist (6.1 ± 3.8 mm *vs.* 9.9 ± 5.2 mm, $p=0.012$) or by automated analysis (4 ± 0 mm *vs.* 9.9 ± 4 mm, $p<0.001$).

Conclusions: Use of three bipolar electrograms recorded from a set of widely spaced electrodes in the right atrium improves the resolution of pace mapping compared to that using P waves from surface electrocardiograms alone.

1. Introduction

Matching the morphology of paced complexes to tachycardia complexes is useful for mapping arrhythmias. In the atrium, pace mapping is useful for focal atrial arrhythmias in order to identify the origin [1], and in macro-reentrant atrial arrhythmias to identify the critical isthmus [2,3]. However, pace mapping in the atrium is limited by its inability to accurately match P-wave morphology obtained on surface electrocardiograms (ECGs), resulting in poor spatial resolution [4]. The objective of this study was to determine if matching the morphology of bipolar electrograms recorded between a set of widely spaced electrodes in the atrium can improve the resolution of pace mapping.

2. Materials and methods

This prospective, cross-sectional, single center study included patients between the ages of 18 and 75 years undergoing an electrophysiology procedure for clinical indications, upon providing informed consent. Patients with structural heart disease, non-sinus rhythm, and with inability to pace the atrium were excluded. The study was performed after the clinical electrophysiology procedure was completed. The study was approved by our Institutional Ethics Committee (No. EC/2011/4/9, approval date 13 September 2011), and written informed consent was obtained from all patients.

Fifteen patients were included in the study (age, 48 ± 13 years; nine men). Six patients underwent ablation of accessory pathways, while the other nine had atrioventricular nodal reentrant tachycardia and underwent slow pathway ablation. A quadripolar

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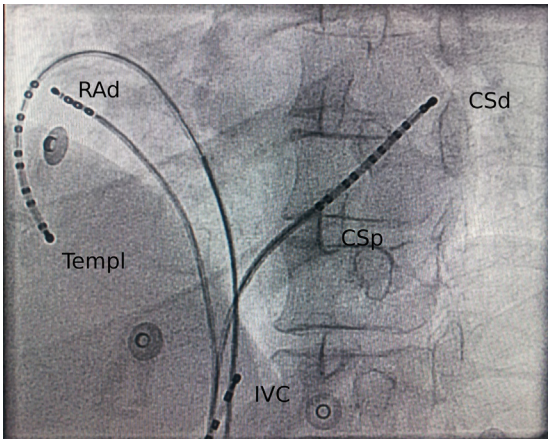

Fig. 1. Position of catheters for the study. Fluoroscopic image in the left anterior oblique view shows the placement of catheters for the study. The decapolar catheter is positioned along the right atrial wall, and the proximal or distal electrode of this catheter is randomly chosen as the template. The electrode pairs for the bipolar electrograms are (1) RAd–CSp, (2) CSp–CSd, and (3) CSd–RAd. The distal electrode of the catheter in the IVC serves as the reference electrode for unipolar pacing. Templ – Template, RAd – Distal right atrial electrode, CSp – Proximal coronary sinus electrode, CSd – Distal coronary sinus electrode and IVC – Catheter in inferior vena cava.

catheter in the right atrial appendage (RAA) and a decapolar catheter in the coronary sinus (CS) were usually used for the electrophysiology study, and these were retained in position. A decapolar catheter with 2–5–2 mm spacing (Webster CS catheter, Biosense Webster, Diamond Bar, CA, USA) was positioned along the lateral right atrium with the distal electrode in the low lateral right atrium, as shown in Fig. 1. Care was taken to ensure that all the electrodes were in contact with the atrial wall, and that the catheter position was stable. A quadripolar catheter was placed in the inferior vena cava to provide a reference electrode for unipolar pacing.

The distal electrode (low lateral right atrium) or the most proximal electrode (high lateral right atrium) of the decapolar catheter was randomly chosen to simulate the tachycardia focus. Unipolar pacing was performed from this electrode with the distal electrode from the catheter in the inferior vena cava as a reference. Pacing threshold was determined at a pulse width of 2 ms. Pacing was performed at 1.5 times the threshold for 15 s at a cycle length of 400 ms and was recorded as a template. Unipolar pacing was subsequently performed from each of the 10 electrodes of the decapolar catheter in a computer-generated random order for 15 s, each at 1.5 times the diastolic threshold. During each of these pacing trains, the 12-lead ECG and a novel set of three widely spaced bipolar electrograms (EGMs) were recorded on the electrophysiology recording system (Labsystem Pro, Bard) at a sampling rate of 1000 Hz. The widely spaced bipolar EGMs were recorded in the following configurations: (a) distal RAA to proximal CS, (b) proximal CS to distal CS, and (c) distal CS to distal RAA. ECG signals were filtered between 0.5 and 250 Hz, while bipolar EGMs were filtered between 30 and 250 Hz. The P-wave morphology in the 12-lead ECG and the bipolar recordings were matched manually by a trained electrophysiologist and by automated computerized analysis.

For manual matching, the observer was presented with the waveforms showing the 12-lead ECG and the three bipolar EGMs printed at a speed of 100 mm/s, with adequate gain to properly visualize the P waves. The observer was blinded to the location of the electrode from which the recording was made. Pace matching was performed by assessing the amplitude of the P wave and comparing the different components of the waveform. The largest deflection was termed the major component, and smaller, additional components were labeled minor components. Accordingly, the match between the template and the recording from any location was classified as follows:

(1) Good match (1 point)
   1. Identical waveforms or
   2. Differences not fitting criteria mentioned below

(2) Partial match (0.5 points) – one of the following minor differences
   1. Differences in amplitude of the major component of at least 25%, but less than 50%
   2. Differences in the shape of the major component
   3. Appearance or disappearance of a minor component
   4. Appearance or disappearance of notching of the major component

(3) No match (0 points)
   1. Two or more minor differences
   2. More than 50% difference in the amplitude of the major component
   3. Appearance or disappearance of the major component

A match score of more than 10 (out of 12) indicated a good match in the 12-lead ECG, while a score of more than 2.5 out of 3 indicated good match in the bipolar EGM. The distance of each electrode from the template location was calculated based on known inter-electrode distances on the decapolar catheter. The minimum distance at which there was no match was the spatial

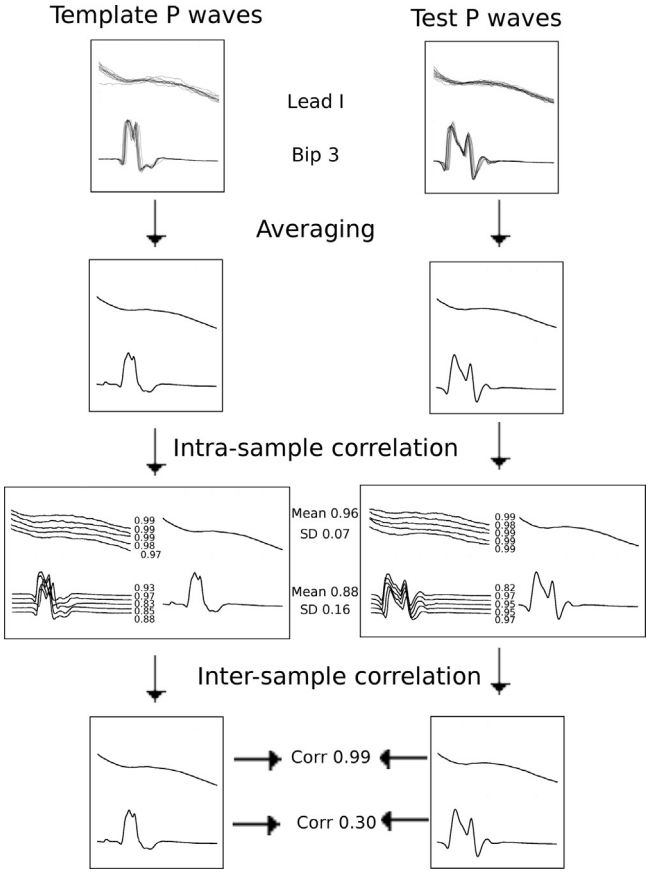

Fig. 2. Algorithm for automated analysis of P wave match score. Schematic diagram illustrates the algorithm used for automated computerized analysis of P-wave match scores. Top row shows P waves from one electrocardiogram lead (Lead I) and one bipolar electrogram recorded from a single patient. P waves are shown from the template and from a test electrode located 7 mm away. The P waves are averaged and intra-sample and inter-sample correlations calculated.

resolution of pace mapping. Spatial resolution was calculated separately for the ECG and the bipolar EGM.

Stored ECGs and EGMs were exported for automated analysis. The details of the algorithm are shown in Fig. 2. Briefly, P waves were separated, and all the P waves from the 15-s recording were averaged for each of the test and template recordings. Intra-sample correlation was calculated as the correlation of P waves within each group to the average P wave, while inter-sample correlation was calculated as the correlation of the average test and template P waves. Based on the inter-sample and intra-sample correlations, a match score was calculated as follows:

$$\text{Match score} = (\text{mean inter} - \text{sample correlation} - \text{mean intra} - \text{sample correlation}) \text{ standard deviation of correlation}$$

This is similar to the z score, with the mean intra-sample correlation providing a "population mean". A score greater than -1 was considered a good match (1 point), a score greater than -2 was a partial match (0.5 points), and a score less than -2 was no match (0 points). Spatial resolution was then calculated in a similar fashion to manual matching. In the example shown in Fig. 2, the inter-sample correlation between the template and a location 2 mm away was high for ECG, suggesting a good match. On the other hand, the correlation was low for the bipolar EGM recorded simultaneously, suggesting no match.

Continuous variables were described as mean and standard deviation and discrete variables as proportions. Spatial resolution of 12-lead ECG and bipolar EGM was compared using Student's paired t-test. All tests were two tailed, and a P-value < 0.05 was considered statistically significant.

3. Results

A total of 15 patients were included in the study. In 10 patients, the distal electrode in the low lateral right atrium was used to simulate the tachycardia focus, and the proximal electrode in the high lateral right atrium was used in the other five. A total of 150 locations were paced in these patients. Stable capture was obtained in 130 (87%) of these, and ECGs and bipolar EGMs were recorded.

With manual matching, the pace match score at the same location as the template was 11.5 ± 0.6 out of 12 for the 12-lead ECG, and 3.0 ± 0.1 for the bipolar EGM. With cutoff values of 10 for the ECG and 2.5 for bipolar EGM, resolution of pace mapping with bipolar EGM (6.1 ± 3.8 mm) was significantly better than that for ECG (9.9 ± 5.2 mm, $P=0.012$). With automated matching, the resolution of pace mapping was again better using bipolar EGM compared to that for ECG (4 ± 0 mm *vs.* 9.9 ± 4 mm, $P < 0.001$). Fig. 3 shows representative P waves from the template and from pacing sites 0, 11, and 33 mm from the focus. At 11 mm, no significant change in ECG P-wave morphology was seen, and the match score was 11.5/12. However, for bipolar EGM, the difference in morphology was clearly seen, and the match score was only 0.5. Tables 1 and 2 summarize the pace match scores at each electrode for manual and automated matching, respectively.

4. Discussion

Based on analysis of P waves recorded during unipolar pacing at known distances from a simulated atrial tachycardia focus, we found that the spatial resolution of pace mapping in the atrium improved with bipolar EGMs recorded from widely spaced electrodes. This improvement was seen both with visual matching by an observer and by automated computerized matching.

Pace mapping is useful for the management of focal atrial tachycardia [5]. Assessment of P-wave morphology is also useful to identify fusion during entrainment of macro-reentrant atrial arrhythmias [2,3]. However, comparing P-wave morphology to assess pace match is inaccurate. Resolution of pace mapping is usually measured as the shortest distance from the tachycardia focus at which the paced morphology is different. In a previous study using unipolar pacing, Man et al. [4] found that the resolution of pace mapping in the right atrium was more than 17 mm. This is in contrast to the better spatial resolution of 5–10 mm in the ventricle [6]. Lower amplitude of the P waves and, sometimes, difficulty in identifying morphology when obscured by the preceding T waves [5] have been implicated as causes of this poor resolution. Paced activation sequence mapping can be used as an alternative [7] to P-wave morphology, but requires the use of multiple electrodes to assess activation. We found that the resolution of pace mapping in the atrium using P waves in the 12-lead ECG was about 10 mm, which is better than previously reported. This could be partly attributable to using printed ECGs recorded at a speed of 100 mm/s and variable gain, instead of 50 mm/s and fixed gain in the previous study. We used changes in morphology only, and did not measure P-wave amplitude and duration as in the previous study [4]. When only P-wave morphology is considered, Mann et al. [4] found differences in morphology in a mean of one lead at a distance of about 10 mm. In the study by Mann et al., inter-electrode spacing was also larger than that in our study, 5 mm in half of the patients, and 10 mm in the other half. This could also have contributed to a larger spatial resolution in their study. The systematic assessment of morphology using the scoring system described by us may have helped improve the resolution of pace mapping.

We present an unusual configuration of bipolar EGMs to assess P-wave morphology. Traditionally, bipolar EGMs are recorded between two closely spaced electrodes in the heart. In some situations, polarity of bipolar EGMs may provide information on the direction of activation [8,9]. With these exceptions, EGM morphology in bipolar EGMs does not provide useful information because the short distance between the recording electrodes and their variable spatial relationships make the information unreliable. While unipolar EGMs present more information in their morphology, the directional information relates only to activation moving towards or away from one point. Therefore, they provide no vectorial information about the activation wavefront. We used bipolar EGMs recorded from two widely spaced electrodes because of the more consistent spatial relationship between the recording electrodes. The three electrode pairs provide relatively orthogonal vectorial information on the activation wavefront. Increasing spacing between bipolar electrodes increases the signal amplitude, with more contribution of far-field electrical activity and a resultant increase in far-field to near-field ratio [10]. By increasing the inter-electrode distance significantly, we obtained bipolar EGMs that were large in amplitude and provided a view of global activation. Using intracardiac bipolar EGMs should also alleviate obscuration by T waves, although this has not been specifically tested and does not occur at slower pacing rates we used in this study. We used unipolar pacing to simulate the tachycardia focus because bipolar pacing may have some variation in the site of origin of depolarization resulting from variable contribution of the anode [11,12].

Automated template matching, available in some electrophysiology systems, has been used to improve pace matching in the ventricle [13]. We found that using automated analysis improved the resolution of pace mapping, especially with bipolar EGMs. The matching algorithms are relatively simple and not computationally intensive, making it possible to implement this on a real-time

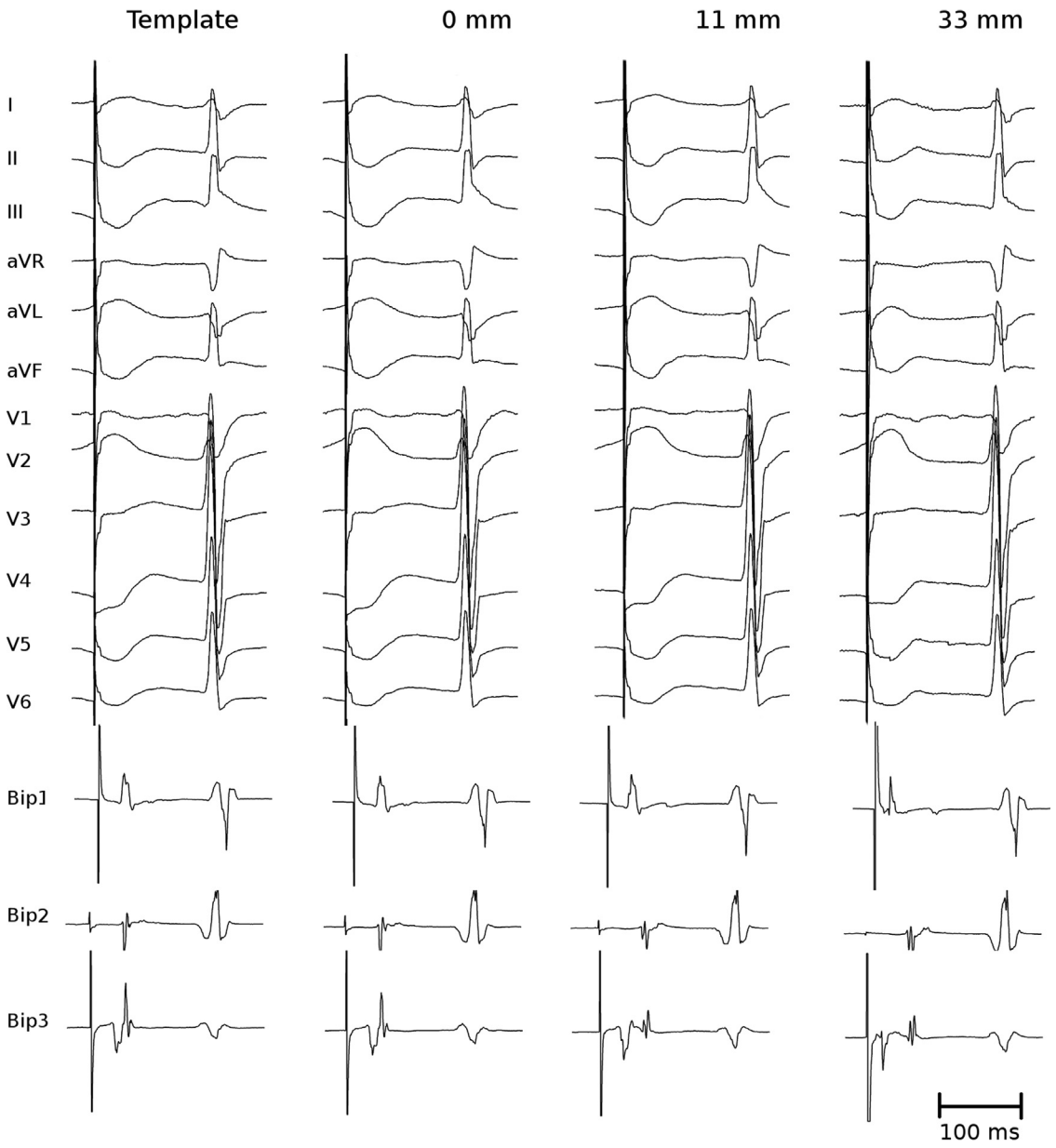

Fig. 3. Representative P waves at different distances from template. Representative P waves in the 12 electrocardiogram leads and the three bipolar electrograms are shown from one of the patients at distances of 0, 11, and 33 mm from the template. At 11 mm from the template, no difference in morphology can be seen in any of the electrocardiogram P waves, whereas major differences are seen in two of the three bipolar leads.

Table 1
Pace match scores between template and test P waves at each electrode using manual matching.

Electrode number (distance from template in mm)	Match score – surface ECG (mean ± sd, max 12)	Match score – bipolar EGM (mean ± sd, max 3)
1 (0)	11.5 ± 0.6	3.0 ± 0.1
2 (4)	10.5 ± 1.4	2.0 ± 0.7
3 (11)	8.3 ± 2.3	1.4 ± 0.9
4 (15)	7.2 ± 2.3	1.1 ± 0.8
5 (22)	7.0 ± 2.7	1.0 ± 0.8
6 (26)	4.7 ± 1.8	0.5 ± 0.5
7 (33)	4.2 ± 2.5	0.5 ± 0.6
8 (37)	3.9 ± 1.8	0.3 ± 0.3
9 (44)	3.1 ± 1.2	0.4 ± 0.5
10 (48)	2.3 ± 1.4	0.5 ± 0.5

ECG, electrocardiogram; EGM, electrogram.

Table 2
Pace match scores between template and test P waves at each electrode using automated matching.

Electrode number (distance from template in mm)	Match score – surface ECG (mean ± sd, max 12)	Match score – bipolar EGM (mean ± sd, max 3)
1 (0)	11.9 ± 0.3	3.0 ± 0.1
2 (4)	9.8 ± 2.5	0.6 ± 0.9
3 (11)	7.2 ± 3.7	0.2 ± 0.4
4 (15)	5.2 ± 3.2	0.1 ± 0.3
5 (22)	4.1 ± 3.2	0.3 ± 0.7
6 (26)	2.9 ± 1.9	0.3 ± 0.8
7 (33)	3.1 ± 1.8	0.4 ± 0.8
8 (37)	3.3 ± 1.6	0.2 ± 0.4
9 (44)	2.5 ± 2.2	0 ± 0
10 (48)	2.6 ± 2.8	0.2 ± 0.5

ECG, electrocardiogram; EGM, electrogram.

basis. Our results suggest that using such automated matching on bipolar EGMs can provide very accurate pace matching. Automated matching would also provide the advantage of being instantaneously available compared to manual matching, which may take a couple of minutes to perform each time.

One limitation of this approach is the need to have catheters in the right atrium and coronary sinus in order to record bipolar EGMs. However, these would already be in place in most patients undergoing mapping and ablation of atrial arrhythmias. We simulated tachycardia focus only in the right atrium, although we tested locations both in the superior and inferior parts of the lateral wall. In a previous study [4], the spatial resolution was poorer in the coronary sinus compared to that in the right atrium. We only used a single cycle length of 400 ms in all patients. However, there is no reason to believe that the results would be significantly different at faster cycle lengths. In fact, at faster cycle lengths, pace mapping using ECG leads would be worse due to merging with T waves, while that using bipolar EGM may be unaltered. Finally, manual matching was only performed by one observer. However, since the results were verified using an objective system of automated template matching, we did not find the need for a second observer to perform the manual matching. We used a pacing output of 1.5 times the diastolic threshold. The size of the virtual electrode is dependent on the stimulus strength. However, the increase in size is roughly related logarithmically to stimulus strength, and is not significant up to outputs of 7 mA [14]. Therefore, we do not expect bias due to large virtual electrode size at the stimulus strengths used in this study.

5. Conclusions

Use of a set of three bipolar EGMs recorded between widely spaced electrodes improves the spatial resolution of pace mapping in the right atrium compared to that with a 12-lead ECG alone. This improvement is seen both with manual matching by a cardiologist and with automated computerized template matching. This improved resolution may make pace mapping a viable tool in the mapping and ablation of atrial arrhythmias.

Conflict of interest

There are no conflicts of interest for any of the authors.

Disclosures

None of the authors have anything to disclose.

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None.

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