Morphology-Based Measurement of Activation Time in Human Atrial Fibrillation

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Abstract

The measurement of the activation time is crucial to allow the correct automatic analysis and classification of intracardiac electrograms recorded in the human atria during atrial fibrillation (AF). This study proposes a method which accounts for the morphology of bipolar signals. After ventricular artifact removal and activation wave recognition, the fiducial point of the activation wave was set at its local barycentre (LB). The method was tested on a set of 30 AF bipolar recordings of increasing complexity class; its performance was compared with that of the traditional methods of maximum peak (MP) or maximum slope (MS) estimation, taking the manual measurements performed by an expert cardiologist as a reference. While for signals with low complexity the agreement with manual analysis was high for all automatic methods, in presence of disorganized AF characterized by complex morphology LB estimation resulted more reliable than MP or MS calculation.

1. Introduction

The analysis of intracardiac recordings acquired during atrial fibrillation (AF) is crucial for the comprehension of the electrophysiological mechanisms responsible for its induction and maintenance, and plays a determinant role in the strategies developed for its clinical treatment. Several methods have been proposed to classify the various types of AF and to determine its degree of organization. For bipolar electrograms, the reference classification scheme is that proposed by Wells [1], in which AF is divided into three principal types according to the morphological features of the detected atrial activation waves. In addition, automatic procedures have been proposed to provide a rapid and objective classification of the different types of AF [2,3] and to quantify its organization [4-6]. Moreover, the analysis of the atrial period (FF interval) has been often used to investigate on the temporal information of the activation processes during AF and to relate such information to the electrophysiological behaviour of the atria [7,8].

The correct automatic measurement of FF intervals and of AF organization requires to develop efficient algorithms for detecting the depolarizing wavefronts and measuring their activation times. Moreover, such algorithms should be applied with equal good results on any AF type and in presence of signal morphology changes. While there is a general agreement about the method to use for signal pre-processing and activation wave recognition [2,6], an unique procedure for designing the activation times from bipolar recordings has not been proposed yet. The methods commonly used are the evaluation of the maximum peak and the maximum slope of the detected activation waves [9]. However, these methods perform a punctual analysis which may provide biased estimates especially on complex AF signals characterized by fragmented morphology.

This study aims to test in human AF an algorithm for measuring the activation time by accounting for the morphological features of the acquired electrograms. The fiducial point is estimated as the barycentre of the activation wave. The performance of this new algorithm is compared with that of the traditional methods, taking the manual measurement performed by an expert cardiologist as reference.

2. Methods

2.1. Patients and data acquisition

The study group consisted of 7 informed patients with paroxysmal AF. A multielectrode basket catheter (EPT, Boston Scientific) with thirty-two bipolar electrodes was inserted via the femoral vein in the right atrium. The exact position of the electrodes was monitored by two orthogonal X-ray images. Bipolar electrograms from 31 intracardiac signals and the lead II of the surface ECG were simultaneously recorded by CardioLab System (Prucka Engineering, Inc.) and digitized at 1 KHz sampling rate and 12 bit precision.

The intracardiac recordings were manually scored and subdivided by an expert cardiologist in type I (AF1), type II (AF2), and type III (AF3) AF according to the Wells

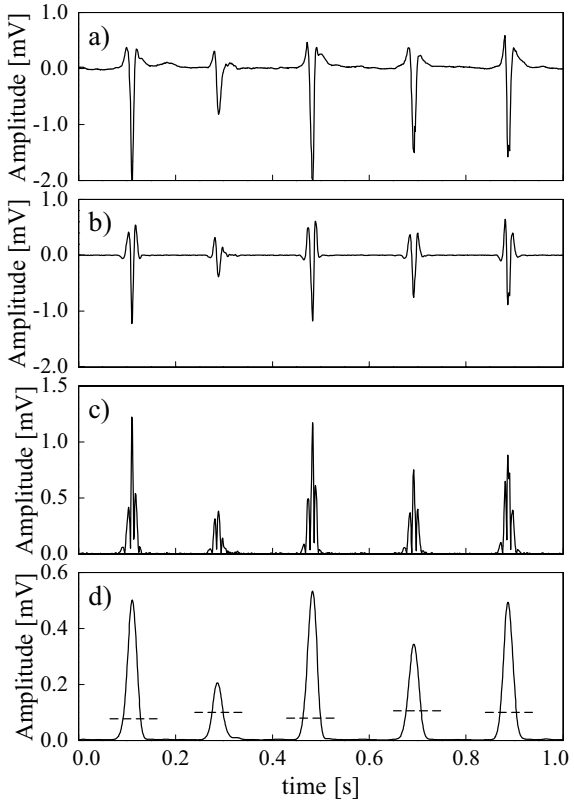

Figure 1. Pre-processing for activation wave recognition. a) original signal, $s(t)$. b) band-pass filtering. c) rectification. d) low-pass filtering to obtain $s_w(t)$.

classification scheme [1]. For each class, ten signals lasting 6 seconds were considered for the analysis.

2.2. Data pre-processing

An averaging technique was used to reduce the effect of the ventricular interference on the atrial recordings [5]. The occurrence times of the ventricular activations were detected from the lead II of the surface ECG [10]. An adaptive template of the ventricular effect was then obtained by averaging atrial signal windows synchronous with the ventricular activation times and subtracted from the atrial signal. The use of an adaptive template rather than a global averaging allowed to better take difference in ventricular conduction during the evolution of the AF episode into account.

2.3. Activation wave recognition

The method for detecting the atrial depolarizations from an atrial electrogram is illustrated in Figure 1. The original atrial signal *s(t)* was bandpass filtered (40-250 Hz, order 40, Kaiser window) to remove baseline shifts and high frequency noise. The modulus of the filtered signal was further low pass filtered (FIR, 20 Hz, order 40, Kaiser window) to extract a time-varying waveform,

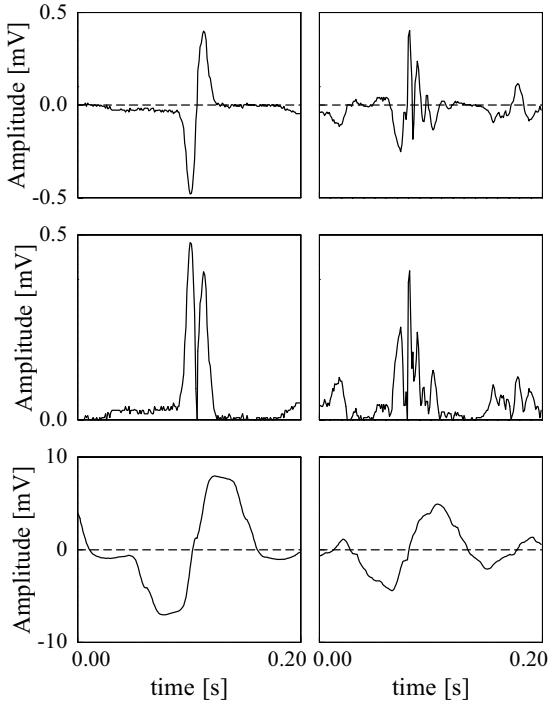

Figure 2. Activation time detection by LB method for regular (left) and irregular (right) activation patterns. Upper panel: original signal, $s(t)$; middle panel: modulus of the signal, $|s(t)|$; lower panel: filtered signal, $s_f(t)$.

sw(t), proportional to the amplitude of the high frequency components of *s(t)* [6]. The atrial depolarizations were then detected by threshold crossing, and the amplitude and position of the corresponding local peaks of *sw(t)* estimated. To account for variability in waveform amplitude, an adaptive threshold (dashed line in Figure 1) accounting for the amplitude of the last ten detected peaks of *sw(t)* with exponentially decreasing weights was set. A blanking period of 55ms was imposed to avoid multiple detections of a single depolarization.

2.4. Activation time estimation

The fiducial point of each detected atrial depolarization, representing the instant of the passage of the propagating wavefront in the area of the acquiring electrodes, was estimated by three different approaches: maximum peak (MP), maximum slope (MS), and local barycentre (LB).

In MP estimation, the fiducial point was set at the time for which the signal exhibited the peak excursion from the baseline. With the MS algorithm, the fiducial point was fixed at the time of the maximum derivative of the analyzed recording. The derivative was calculated by a low-pass filter (FIR, 100 Hz, order 128, least squares), obtained from a filter with linear complex frequency response followed by a low pass filter (100 Hz) to

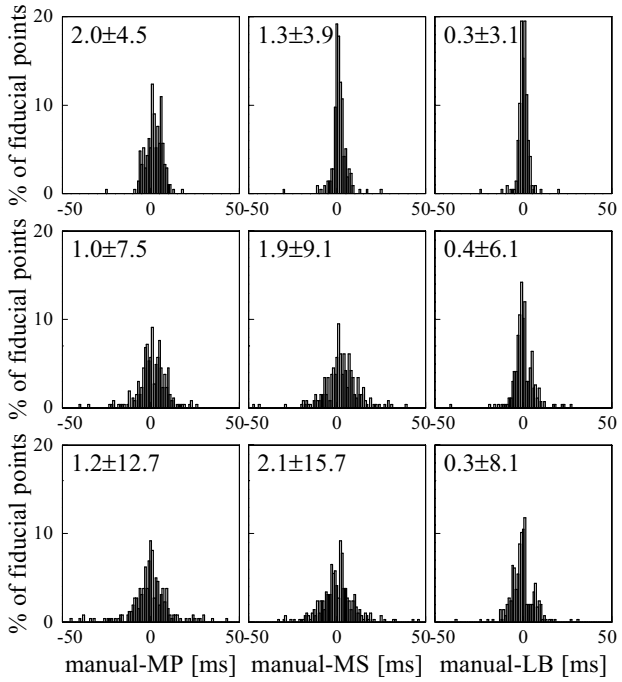

Figure 3. Differences between manual and automatic activation times for AF1 (upper panels), AF2 (middle panels), and AF3 (lower panels) signals. For each panel, differences are indicated as mean ± SD, expressed in ms.

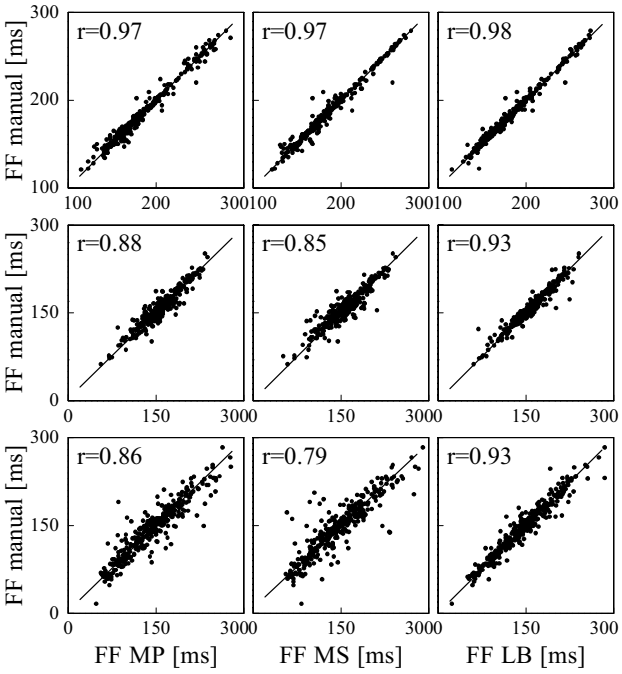

Figure 4. Linear correlation between manual and automatic FF intervals for AF1 (upper panels), AF2 (middle panels), and AF3 (lower panels) signals. Values of the correlation coefficient are indicated for each panel.

attenuate high-frequency noise.

In LB calculation, the barycentre of the activation wave was defined as the time that divided in two equal parts the local area of the modulus of the signal. To detect the barycentre, a moving average non-casual filter with 90 coefficient was applied to the absolute value of the original electrogram *s(t)*:

$$s_f(t) = \sum_{i=0}^{44} |s(t-i)| - \sum_{i=1}^{45} |s(t+i)| \qquad (1)$$

For each detected depolarization, the activation time was set on the positive zero crossing of $s_f(t)$ which was closer to the local peak of $s_w(t)$ (Figure 2).

3. Results

To evaluate the performance of the proposed method, the occurrence times of the atrial depolarizations detected by LB, MP, and MS methods were compared by taking the manual measurement as reference. Each of the three automatic measures was related to the manual calculation by analyzing the difference between the activation times and by performing a linear regression analysis between the FF intervals. A total of 1067 activation waves were detected in the analyzed signals. Results are summarized in Figure 3 and Figure 4. For each AF type, the distribution of the differences between automatic and manual measurements showed mean value closer to zero and lower dispersion when LB estimation was performed instead of MP and MS. The better agreement of LB method with manual analysis was also demonstrated by the higher values of the correlation coefficient derived from regression analysis. Moreover, both distribution and regression analyses evidenced a decrease of accuracy of MS and MP estimates at increasing AF complexity. On the contrary, LB estimation kept the agreement with the reference measure also for AF2 and AF3 signals.

The capability of the proposed approach to capture beat-to-beat variations of atrial activation rate is depicted in Figure 5, where the LB-based measurement of FF intervals during an AF episode showing spontaneous changes in complexity is reported.

4. Discussion

The designation of the occurrence time of the local activation from bipolar intracardiac signals acquired during human AF is fundamental to electrophysiological mapping and for evaluating the arrhythmia organization. Thus, algorithms determining with high precision the

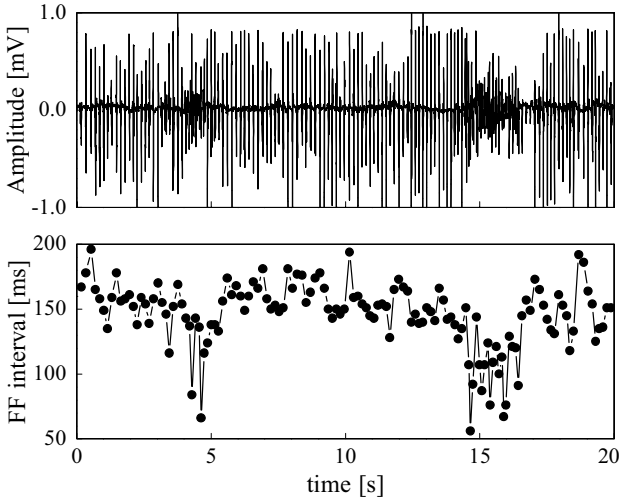

Figure 5. Time course of the FF intervals calculated by the LB approach during an AF episode with spontaneous changes in rhythm.

atrial activation time in different rhythm conditions are mandatory. This study introduced a new method considering the signal morphology. Results depicted in Figures 3 and 4 evidenced that the agreement with the expert estimation of the activation times was higher for the proposed LB approach than for traditional MP and MS methods, both in terms of difference between the occurrence times and of correlation between the FF intervals. The better performance of the LB method was particularly evident for AF2 and AF3 signals, while for AF1 signals the agreement with manual measure was high and comparable for all automatic methods. Thus, barycentre calculation seems particularly indicated in presence of complex AF episodes characterized by fragmented activations with complex morphologies. On the other side, the suitability of morphological approaches with respect to estimates considering only one peak or one slope has also been previously addressed [9,11].

The comparison emphasized the structural differences between the traditional activation time estimation and our method. In AF1 signals, the regularity of the electrical activation makes possible for all methods to properly estimate the activation time, intended as the instant of activation of the center of the bipole. In AF2 and AF3 signals, exhibiting fragmented activations with troubled or absent isoelectric line, the punctual analysis performed by MP and MS methods are often corrupted by the local features of the depolarizing electrical wavefront. On the contrary, LB estimation accounts for the whole shape of the activation wave and then is less sensitive to short modifications of the propagating wavefront. This could explain the better agreement with manual inspection found for morphological estimates than for punctual ones in presence of disorganized AF.

In conclusion, our results suggest that the proposed method constitutes a precise way for determining the occurrence time of the activation waves during AF, even in presence of complex episodes with rapid variations in rhythm. The good agreement with the reference manual appraisal and the possibility to automatically implement the method suggest its use for the online measurement of the FF intervals and of the degree of organization of AF.

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