Wavelet-Based Electrogram Onset Identification for Ventricular Electroanatomical Mapping

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Abstract

Identification of the earliest activation area is a common task in focal tachycardia catheter ablation treatments. In these procedures the detection of the electrogram (EGM) activation onset during electroanatomical mapping (EAM) helps to define the ablation target area. However, EAM systems do not automatically detect the EGM activation onset and this is currently done manually in clinical routine, thus highly dependent on observer experience and very time consuming.

In this work we propose a method that combines surface electrocardiogram (ECG) information with EGM signals in order to determine each activation onset for helping the determination of the ablation target area. The algorithm detects those instants from the wavelet decomposition of the EGM signal envelope using the QRS complex width as a reference search window. The automatically detected activation onsets were compared with those made manually during the intervention by an expert technician, obtaining a difference of 4.0 $\pm$ 13.7 ms evaluated in 10 patients suffering from ventricular extrasystole beats, in a total of 2163 EGM mapping points.

1. Introduction

Catheter ablation is the elective treatment of common arrhythmias when they become resistant to antiarrhythmic drugs. In these procedures an EAM system is frequently used to guide the ablation. Those systems combine a 3D anatomical view of the patient's heart with the electrical properties of invasive EGM signals obtained with catheters. The identification and ablation of the earliest activation area is one of the aims of ablation procedures specially in focal tachycardias [1].

Local activation time (LAT) is a helpful measurement which can be defined as the time difference between a reference and the instant when the myocardium area under study is electrically activated. Different LAT definitions are found in the literature according to the acquisition process, i.e. unipolar or bipolar EGMs. In unipolar EGMs the maximum negative slope of the signal coincides with the upstroke of the cardiac action potential and therefore, with the true activation time [2]. However, unipolar EGMs are not so commonly used in the clinical practice because they are prone to be disrupted by other electrical sources. In bipolar EGMs, a common surrogate of the LAT are the maximal or minimal peak of the signal and the maximal negative slope [3]. In a recent study, an algorithmic method using a 4-state machine for detecting the activation onset was proposed for atrial tachycardias [4].

The CARTO® system (*Biosense-Webster Inc.*) is one of the most used EAM systems. However, it only locates the local single maxima of the EGM in a window of interest. This forces the expert technician to manually mark in every EGM signal the time instant when the activation starts. This is a time consuming and observer-dependent procedure achieved in stressing conditions. Once done for all EGMs, it would be straightforward to estimate the earliest activation area for guiding the ablation procedure.

In this work we propose a method which combines surface ECG information with the wavelet decomposition of the EGM activation envelope in order to reliable and automatically delineate its onset and end.

2. Materials

We studied 14 electroanatomical maps from 10 patients suffering from ventricular extrasystole beats admitted for

ablation procedure at Hospital Clínic (Barcelona, Spain). During the intervention, the earliest activation area was determined and ablated until the termination of the arrhythmia.

Each map was acquired with the CARTO® 3 system. The total number of studied mapping points was 2163 (155 $\pm$ 68 points per map). Each point includes standard 12-lead ECG signals and bipolar EGM signals from a NaviStar Thermocool® catheter (*Biosense-Webster Inc.*) 16-500 Hz band-pass filtered with a 50 Hz notch filter. Those signals were acquired at 1 kHz sampling frequency during 2.5 seconds, assuring that the contact of the catheter tip with the endocardial wall of the heart was stable. The distal bipolar EGM signal was used for EAM during the intervention and therefore for calculations in this work.

For assessment of the proposed methodology, the EGM activation onset measured by an expert technician during the procedure (we will refer to it as "*on-line*") is used as reference.

3. Methods

3.1. Signal envelope

EGM signals present a large variety of morphologies due to the passing of the different activation wavefront through the catheter sensors and the relative position between the focus and the electrodes. Thus an overall view of the signal is needed in order to minimize the shape variation of the EGM signal.

Let an EGM activation signal $x[n]$ be modelled as a positive valued low-pass signal $b[n]$ modulated by a cosine with modulation frequency ω_m and phase angle ϕ:

$$x[n] = b[n] \cdot cos(\omega_m n + \phi). \quad (1)$$

A well-known technique from the field of communications [5] can be used in order to extract the envelope $b[n]$ by means of the analytic signal of $x[n]$ defined as:

$$x_a[n] = x[n] + j\breve{x}[n], \quad (2)$$

where j is the imaginary unit and $\breve{x}[n]$ stands for the Hilbert transform of $x[n]$. Therefore the analytic signal $x_a[n]$ represents a frequency-shifted version of the envelope $b[n]$, which can be easily obtained without previous knowledge of ω_m or ϕ by means of the absolute value

$$b[n] = |x_a[n]| = \sqrt{x[n]^2 + \breve{x}[n]^2}. \quad (3)$$

The analytic signal was implemented using the *hilbert.m* function of Matlab (*The MathWorks Inc.*). Figure 1 shows an example of the envelope computation of a real EGM signal.

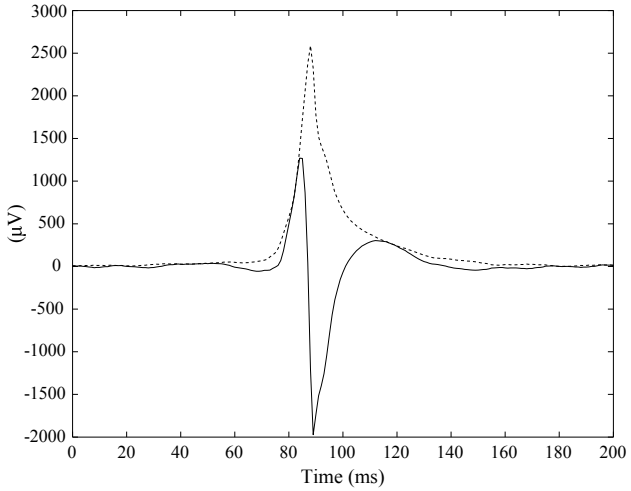

Figure 1. Example of a ventricular EGM activation in bold line and its envelope in dashed line.

3.2. The wavelet transform

The wavelet transform (WT) is a decomposition of the signal as a combination of a set of basis function obtained by dilation a and translation b of a single prototype wavelet $\psi(t)$. Thus the WT of a signal $x(t)$ is defined as

$$W_a x(b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi \left(\frac{t-b}{a} \right) dt, a > 0, \quad (4)$$

where the scale parameter a modify the bandwidth and time resolution at each scale. If the prototype wavelet $\psi(t)$ is the derivative of a smoothing function $\theta(t)$, the WT of a given signal $x(t)$ at scale a can be written as

$$W_a x(b) = -a \left(\frac{d}{db} \right) \int_{-\infty}^{+\infty} x(t) \theta_a(t-b) dt, \quad (5)$$

where $\theta_a(t) = (1/\sqrt{a})\theta(t/a)$ is the scaled version of the smoothing function. Therefore the WT at scale a is proportional to the derivative of the filtered version of the signal with a smoothing impulse response at the current scale a. Thus the zero-crossings of the WT correspond to the local maxima or minima of the smoothed signal at different scales, and maximum values of the WT are associated with maximum slopes in the smoothed signal.

For implementation, the WT was discretized by means of the *dyadic discrete wavelet transform* using the *algorithme à trous* [6] which allows to preserve the time resolution of the signal representation by removing the decimation stages and interpolating the filter impulse response of the previous scale in Mallat's algorithm [7].

In this work, the used prototype wavelet, $\psi(t)$, was the derivative of a quadratic spline which transfer function shows a low-pass filter differentiation behavior and was

previously used in ECG detection and delineation [8] and atrial fibrillation cycle length analysis [9].

3.3. Detection algorithm

The CARTO® system acquires the signal referenced to a beat centered at time 2000 ms of each recorded excerpt. Therefore, in order to accurately locate the ventricular EGM signal from the beat of interest, a single-lead wavelet-based QRS detector and delineator [8] was applied and a global multi-lead delineation is obtained using rules as described in [10].

Thus, three instants for each reference beat were identified: the onset of the QRS complex (n_o), the QRS fiducial point which usually corresponds with the R wave (n_f) and the QRS complex end (n_e). Those instants are shown in the upper trace of Figure 2. In order to characterize the EGM activation, we define the window, S, from n_o to n_e which was extended 30 ms in both ends for EGM activation location and up to 60 ms if needed.

The algorithm is based on the multi-scale approach in [8], whose aim is to locate a set of local maxima and minima exceeding a threshold across the different scales of the WT called *"Maximum Modulus Lines"* (MML). The derivative properties of the WT together with the positive low-pass properties of the signal envelope allow to locate the main peak of the EGM envelope, denoted as n^{EGM}, which we called *"activation main wave"*. This main wave is represented by the zero-crossings at scale $a = 2^1$ between a pair of local maxima and minima crossing a threshold defined by the RMS value within S of the scale $a = 2^4$ which is related with the global EGM envelope shape.

The EGM activation onset and end (n_o^{EGM} and n_e^{EGM}) were located as the first sample below or above a threshold defined by the amplitude percentage of the corresponding positive or negative MML at scale $a = 2^2$ which is related to the slopes of the EGM envelope.

Figure 2 illustrates the algorithm for EGM delineation and the LAT definition used in this work, computed as the time difference between the EGM activation onset and the R wave of the QRS complex.

4. Results

The assessment of the results was made by comparing the LAT obtained with our algorithm with those manually obtained during the ablation procedure (i.e. under stressing conditions) by an expert technician.

The obtained mean difference $\pm$ standard deviation (SD) between the automatic annotations and the on-line ones for all the studied points is 4.0 $\pm$ 13.7 ms. The Bland-Altman plot of Figure 3 shows the agreement between both set of measurements with the 96% of studied points within

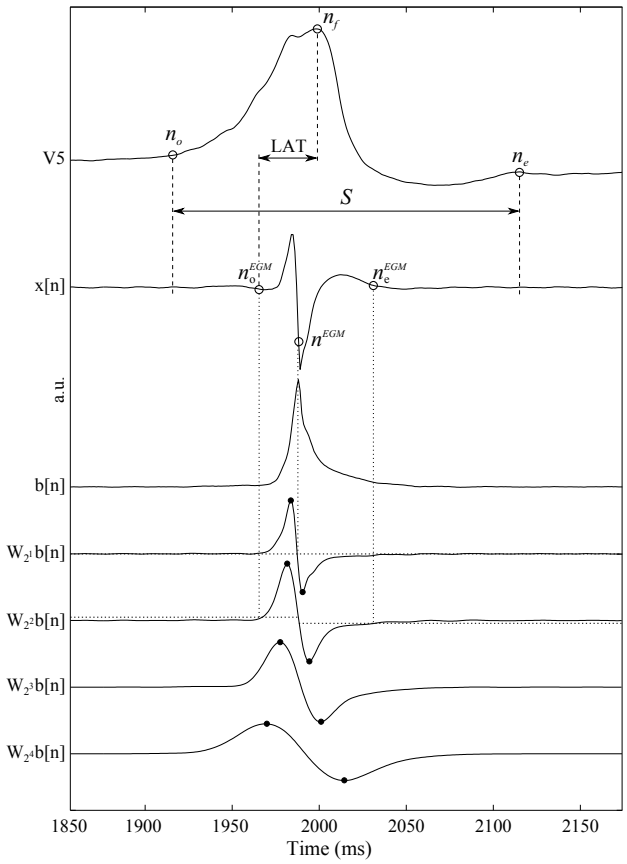

Figure 2. Surface ECG V5 lead, EGM signal, x[n], its envelope, b[n], its four scales of the wavelet transform $W_{2^k}b[n]$, $k = 1 \cdots 4$, the detected MMLs in black dots, the main window S, the relevant time instants detected by the algorithm and the LAT calculation.

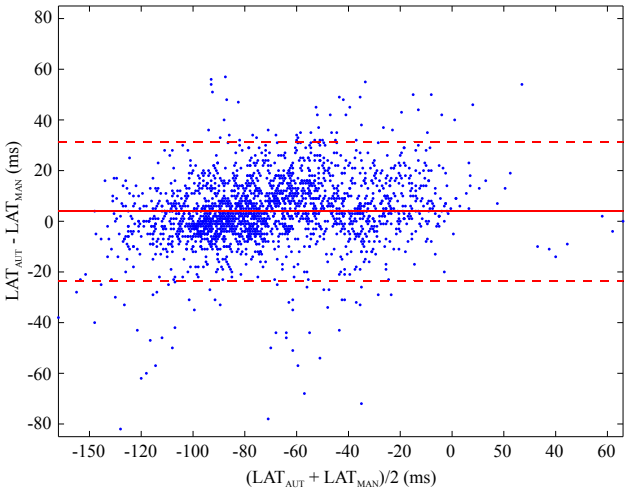

Figure 3. Bland-Altman plot of the difference between the automatic LATs (LAT_{AUT}) and the on-line manual LATs (LAT_{MAN}) with the mean difference in red bold line $\pm$ twofold SD in red dashed line.

the mean difference ± twofold SD. In addition, 64% and 87% of the studied points shows a difference less than 10 ms and 20 ms respectively.

Table 1 shows the difference between both set of measurements for each map individually. In general, we observed that the automatic algorithm provided slightly later LATs than the manual annotations and the automatic detection is stable in terms of the SD of the difference.

Table 1. Difference between the on-line manual LATs and the automatic ones for each studied map (mean ± SD).

Map	Points (#)	Difference (ms)
1	144	2.1 ± 12.3
2	117	3.9 ± 10.7
3	163	7.6 ± 11.3
4	195	3.5 ± 8.3
5	220	7.5 ± 11.3
6	264	1.0 ± 8.7
7	49	4.9 ± 15.9
8	208	6.8 ± 11.1
9	173	6.7 ± 15.4
10	199	8.7 ± 14.1
11	206	0.2 ± 20.1
12	98	1.5 ± 17.6
13	87	3.2 ± 11.9
14	40	-11.4 ± 20.6
Total	2163	4.0 ± 13.7

5. Discussion and conclusion

Identification and ablation of the earliest activation area is the aim of focal tachycardia ablation procedures. However, EAM systems do not automatically locate the EGM activation onset and this should be made manually by the technician during the operation, thus it is very time consuming and highly dependent of the observer experience and stress conditions.

In this work, a new method for automatically determine the onset and end of ventricular EGM signals is proposed. The method combines information of the surface ECG with the EGM signals based on the WT of the EGM envelope. For assessment of the proposed methodology, the automatically detected time instants were compared with those made manually during the procedure by an expert technician. Results show that the proposed method automatically estimate LATs with precision comparable to the on-line manual ones used for diagnosis and ablation.

Future validation of the proposed method with manual annotations obtained off-line and in non-stressing conditions will be introduced as well as the delineation of other waves for helping on the treatment of other ventricular arrhythmias.

Acknowledgments

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