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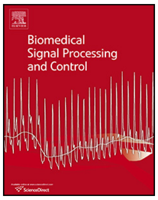

Algorithmic detection of the beginning and end of bipolar electrograms: Implications for novel methods to assess local activation time during atrial tachycardia

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ABSTRACT

Activation mapping is required to effectively ablate atrial tachycardia (AT). Conventional tools to assess local activation time (LAT) are based upon the peak of the bipolar electrogram (B-EGM, LAT_{Peak}) and the maximal negative slope of the unipolar electrogram (U-EGM, $\text{LAT}_{\text{Slope}}$). Bipolar electrograms are influenced by wavefront direction, bipole orientation, and inter-electrode spacing causing ambiguity in peak detection, whereas unipolar electrograms are disturbed by the presence of far-field signals. We developed a new algorithm to detect the beginning and end of bipolar electrograms (t_{begin} and t_{end}). Then, we introduced new LAT methods related to the onset of B-EGMs ($\text{LAT}_{\text{Onset}}$), the center of mass of B-EGMs (LAT_{CoM}), and the slope of U-EGMs within a pre-defined window ($\text{LAT}_{\text{Slope-hybrid}}$).

In total 3752 recordings from 31 AT patients were retrospectively analyzed. The signal-to-noise ratio (SNR) for B-EGMs was calculated to differentiate algorithmically high from low quality electrograms (HQ and LQ). In a subset of 328 B-EGMs, five experts validated the t_{begin} as determined by the algorithm by visual rating. The newly developed LAT methods were compared to the conventional LAT methods and to one another (Bland–Altman plots) in both HQ ($n = 3003$) and LQ EGMs ($n = 749$).

The t_{begin} algorithm was accurate (deviation $< \pm 10$ ms) in 96 ± 4% of HQ and 91 ± 8% of LQ B-EGMs. BA plots revealed the following difference (bias) and variation in HQ and LQ EGMs respectively: (1) $\text{LAT}_{\text{Onset}}$ vs. LAT_{Peak}: 27 ± 30 ms and 24 ± 62 ms; (2) LAT_{CoM} vs. LAT_{Peak}: 0 ± 16 ms and 2 ± 38 ms; (3) $\text{LAT}_{\text{Slope-hybrid}}$ vs. $\text{LAT}_{\text{Slope}}$: 1 ± 32 ms and 15 ± 110 ms; (4) $\text{LAT}_{\text{Onset}}$ vs. LAT_{CoM}: 22 ± 24 ms and 18 ± 22 ms; (5) $\text{LAT}_{\text{Onset}}$ vs. $\text{LAT}_{\text{Slope-hybrid}}$: 16 ± 18 ms and 13 ± 22 ms; and (6) LAT_{CoM} vs. $\text{LAT}_{\text{Slope-hybrid}}$: 5 ± 20 ms and 4 ± 18 ms.

In the present study, we introduced three new methods to assess local activation time in AT, based upon an algorithm detecting accurately the beginning and end of the B-EGM complex. BA analysis of the new methods showed similar variation in high and low quality EGMs, suggesting that they introduce less ambiguity than the conventional peak method. $\text{LAT}_{\text{Onset}}$ consistently yielded an earlier activation moment. $\text{LAT}_{\text{Slope-hybrid}}$ – by blanking far-field potentials – seems to be the optimal method for detection of the maximal negative slope in U-EGMs. Interestingly, LAT_{CoM} in B-EGMs coincided with the maximal negative slope in U-EGMs, suggesting its physiological sense and future use. The new LAT methods can be implemented in real-time mapping applications.

1. Introduction

Catheter ablation is an effective non-pharmacological method to treat symptomatic atrial tachycardia (AT). Combining 3D anatomical maps of the atria with assessment of local activation time (LAT) provides a powerful tool (electro-anatomical mapping) to guide ablation. Electro-anatomical mapping is usually performed by sequential point-by-point acquisition of coordinates and electrograms.

Abbreviations: AT, atrial tachycardia; B-EGM, bipolar electrogram; CL, cycle length; CNT, counter; CoM, center-of-mass; CS, coronary sinus; HQ, high quality; LAT, local activation time; LQ, low quality; ROC, receiver operating characteristic; SNR, signal-to-noise ratio; U-EGM, unipolar electrogram.

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Assessment of LAT can be performed using unipolar and bipolar electrograms. Considering unipolar electrograms (U-EGM), Spach et al. [1,2] showed that the maximum negative slope of U-EGM coincides with the upstroke of the action potential and the true moment of activation. U-EGMs, however, are susceptible to far-field potentials and are therefore rarely used in clinical practice [3]. For bipolar electrograms (B-EGM), the maximal positive and/or negative peak and the maximal negative slope ($-dV/dt$) have been suggested as fiducial markers for LAT [4,5]. B-EGM morphology, however, is influenced by wavefront direction, bipole orientation, electrode size, and inter-electrode spacing [6]. As such, assessment of LAT based upon the B-EGM peak or slope can introduce ambiguity, especially when electrograms become more complex due to multiple wavelets, showing various peaks and variation in morphology.

We aimed to develop an automated algorithm to reliably detect the beginning (t_{begin}) and the end (t_{end}) of the activation complex in the B-EGM. Then we introduced new methods to determine LAT within the time window demarcated by the t_{begin} and t_{end}: (a) the onset of B-EGM ($\text{LAT}_{\text{Onset}}$), (b) the center of mass of B-EGM (LAT_{CoM}), and (c) the slope of U-EGM ($\text{LAT}_{\text{Slope-hybrid}}$).

2. Methods

A database of 3752 recordings was collected from 31 patients who underwent catheter ablation of AT guided by the CARTO® system (Biosense-Webster, Diamond Bar, CA, USA) at the University Hospital of Ghent and Sint-Jan Hospital Bruges. An irrigated-tip ablation catheter with a distal 3.5 mm tip and three 1 mm ring electrodes spaced by 2-5-2 mm (Navistar® Thermocool, Biosense-Webster, Diamond Bar, CA, USA) was used for both mapping and ablation. A decapolar catheter was placed in the coronary sinus and the proximal bipole was selected as a reference for activation mapping. The ablation strategy consisted of targeting the area of earliest activation for focal tachycardia and creation of a line of block for macro-reentry tachycardia. Prior to ablation, high-density point-by-point mapping (122 ± 45 points) was performed. Care was taken to have (1) a stable position of the distal bipole for >3 s, and (2) a homogeneous spatial distribution of the recorded EGMs. A U-EGM (tip electrode, band-pass filtered 0.5–500 Hz) and a B-EGM (tip minus ring electrodes, band-pass filtered 30–240 Hz) were recorded for 2.5 s from each site with a sampling rate of 1000 Hz. After the procedure, all electrograms were extracted from the system and offline analysis was performed in Matlab v7.10 (The MathWorks, Inc., Natick, MA, USA). All algorithms were developed and executed on a regular Microsoft Windows PC with Intel Core 2 CPU clock rate of 3.0 GHz. On average, 120 EGMs (corresponding to one high-density map) were analyzed within 500 μs. From this database, 328 recordings from four random patients were used for visual validation of the t_{begin} algorithm. For comparison of the LAT algorithms, all 3752 electrograms were analyzed. Data is presented as mean ± SD unless otherwise stated. A P value < 0.05 was considered statistically significant. Bland–Altman (BA) plots were constructed to evaluate the variation between the conventional and the new methods. The study was approved by the ethics committee at the University of Ghent.

3. Algorithm to detect the t_{begin} and t_{end} of the activation complex in B-EGM

An algorithm was developed to detect the beginning (t_{begin}) and end (t_{end}) of the activation complex of the B-EGM. Fig. 1 shows a block diagram of the t_{begin} and t_{end} algorithm and the LAT methods. Two main steps can be identified; (1) detection of the t_{begin} and t_{end} of the activation complex, and (2) determination of LAT by three different methods and signal-to-noise ratio (SNR).

The different steps of the t_{begin} and t_{end} algorithm are plotted in Figs. 2 and 3. In the first step (Fig. 2, panel A), an A-wave detection algorithm was used to calculate the A-A intervals in the 2.5 s reference recording (i.e. B-EGM recorded at the coronary sinus). The average of A-A intervals was taken as the atrial tachycardia cycle length (ATCL). For each 2.5 s recording, the second last complex was analyzed. A mapping window was calculated (ATCL minus 10 ms to prevent overlapping from the previous and following beats) and centered around the A peak (i.e. 0 ms) on the reference EGM. Next, the detection threshold was determined based upon the B-EGM noise level calculated within the isoelectric windows before and after the complex. To determine the isoelectric windows, first the B-EGM of interest (Fig. 2, panel B) was smoothed and rectified using a 2–15 Hz second order bi-directional Butterworth band-pass filter (Fig. 2, panel C). The band-pass 2–15 Hz was chosen to remove high frequency components from the signal, thus generating a smoothed signal to clearly identify the isoelectric windows. Then, the minimum signal threshold was calculated as the 5th percentile (P5) of the B-EGM amplitudes plus 20% of the top 95th percentile (P100–P5) amplitudes (Fig. 2 panel D). The intersection points between the minimum signal threshold and the signal were used as markers to demarcate the signal window and (by exclusion) the isoelectric windows before and after the signal complex (Fig. 2, panel E). For all subsequent steps, the original unfiltered B-EGM of interest (Fig. 2 panel B) was differentiated, filtered (second order bidirectional Butterworth band-pass filter 5–300 Hz), and rectified (Fig. 2 panel F). The band-pass 5–300 Hz was chosen to eliminate low frequency components and preserve the sharp high frequency component of the noise. The noise level was calculated as the maximum peak amplitude in the isoelectric windows (Fig. 2, panel G). Finally, a detection threshold was then calculated as the 98th percentile of the noise level (Fig. 2, panel H).

A 4-state machine algorithm then was used to determine the beginning and the end of the activation complex in the 5–300 Hz filtered and rectified B-EGM (Fig. 3 upper panel). Starting at the peak amplitude within the mapping window, the filtered B-EGM was scanned backwards to reach the beginning (t_{begin}) of the complex (Fig. 3, lower left panel). The end of the complex (t_{end}) was detected by reversing the B-EGM and applying the same algorithm (Fig. 3, lower right panel).

The state machine starts and remains in State_A until the detection threshold is underceeded. When crossing the detection threshold, an incremental counter (CNT) is initialized and the state machine moves to State_B. In State_B, back scanning continues as long as the signal is below the detection threshold. When CNT reaches a predefined maximum (CNTSTATE_B), the algorithm moves to State_C. While in State_B, and the signal rises above the detection threshold, the algorithm moves back to State_A. The state machine may switch multiple times between states A and B before switching to State_C. Once in State_C, the state machine cannot switch back to State_B. In State_C, back scanning continues as long as the signal is below the detection threshold and CNT is below CNTSTATE_C. When CNT reaches CNTSTATE_C while the signal is still under the detection threshold, the algorithm terminates and assigns the last detected moment above the detection threshold as the t_{begin}. While in State_C, if the signal crosses the detection threshold, the state machine switches to State_D and a secondary counter (GCNT) is initialized to zero. In State_D, GCNT is incremented as long as the signal remains above the detection threshold. When GCNT reaches the counter preset value (CNTSTATE_D), the state machine moves back to State_A. If the signal crosses the detection threshold while in State_D, the algorithm terminates and assigns the last time instance above the detection threshold as the t_{begin}.