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Spatiotemporal model-based estimation of high-density atrial fibrillation activation maps

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ABSTRACT

Examination of activation maps using multi-electrode array (MEA) sensors can help to understand the mechanisms underlying atrial fibrillation (AF). Classically, creation of activation maps starts with detection of local activation times (LAT) based on recorded unipolar electrograms. LAT detection has a limited robustness and accuracy, and generally requires manual edition. In general, LAT detection ignores spatiotemporal information of activation embedded in the relation between electrode signals on the MEA mapping sensor. In this work, a unified approach to construct activation maps by simultaneous analysis of activation patterns from overlapping clusters of MEA electrodes is proposed. An activation model fits on the measured data by iterative optimization of the model parameters based on a cost function. The accuracy of the estimated activation maps was evaluated by comparison with audited maps created by expert electrophysiologists during sinus rhythm (SR) and AF. During SR recordings, 25 activation maps (3100 LATs) were automatically determined resulting in an average LAT estimation error of -0.66 ± 2.00 ms and a correlation of $\rho_s = 0.98$ compared to the expert reference. During AF recordings (235 maps, 28226 LATs), the estimation error was -0.83 ± 6.02 ms with only a slightly lower correlation ($\rho_s = 0.93$). In conclusion, complex spatial activation patterns can be decomposed into local activation patterns derived from fitting an activation model, allowing the creation of smooth and comprehensive high-density activation maps.

1. Introduction

Atrial fibrillation (AF) is one of the most common arrhythmias, responsible for one third of all hospitalizations at cardiac arrhythmia units [1], with an increasing prevalence due to aging of the population [2,3]. Moe et al. [4] first proposed the wavelet hypothesis underlying the initiation and perpetuation of AF, describing the presence of multiple propagating wavelets sustaining the fibrillation process, validated later by Allessie et al. [5,6]. Other proposed mechanisms include driving foci, mainly located at the pulmonary veins [7], re-entrant circuits, rotors [8,9] and trans-mural conduction of fibrillation waves between epicardial and endocardial atrial layers [10,11]. However, mechanisms underlying the initiation and perpetuation of AF are not yet fully understood [8], limiting the optimal treatment of patients.

Activation mapping is the most commonly used method for visualization and study of cardiac arrhythmias [12]. During hemodynamically stable and regular tachycardia, activation maps can be created after sequential recording of electrograms (EGM) and detected local activation times (LAT) can be referred against a fiducial point in a simultaneously recorded surface or intracardiac signal [13]. However, during irregular tachycardia like AF, simultaneous mapping is needed due to the non-repetitive nature and complexity of the arrhythmia [8]. Multi-electrode mapping catheters such as PentaRay and Lasso (*Biosense Webster, Inc. Diamond Bar, CA, USA*) or the Constellation full contact basket catheter (*Boston Scientific, Inc. Natick, MA, USA*) lack spatial resolution during more complex activation of the atrium due to electrode sparsity and bad wall contact [14]. For high-density mapping of more complex AF, a high-density multi-electrode array (MEA) mapping sensor will be needed [8].

In this study, unipolar electrograms (u-EGM) were recorded using a MEA mapping sensor in direct contact to the epicardial wall of the atrium during open chest surgery. The recorded signals are

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displayed in a matrix related to the location of the electrodes on the MEA sensor. This will allow constructing activation maps which show the propagation of cardiac activation [6,8].

The construction of activation maps involves several processing steps including denoising, baseline correction, far field R-wave cancellation and detection of activation times followed by an error rejection process. Detection of LATs is related to the u-EGM steepest negative slope (dV/dt) as a result of an activation wave under-passing the recording electrode [15,16]. Activation maps are constructed by combining LATs detected from each of the electrodes on the mapping array. However, this procedure ignores the information embedded in the morphology of the u-EGM signal, hence not used for the creation of high-density activation maps.

Detailed cardiac electrophysiological modeling provides insight in the physiology underlying cardiac arrhythmias and serves as a tool for a better diagnosis and interpretation of experimental data [17]. Those models describe the ion currents flowing through the myocardial cell membrane (e.g. [18,19]) embedded in realistic structures and geometries of the human heart [17]. Less detailed models of cardiac propagation provide a less time-consuming alternative to represent the cardiac activation propagation. Equivalent source model uses current sources and densities to calculate the potentials, hence describing the activation propagation as a uniform double layer (UDL) model [20].

In this paper, a unified spatiotemporal approach for estimation and construction of high-density activation maps is presented. The proposed method fits an activation pattern model to acquired cardiac activity in order to reconstruct the complete activation map as the combination of contributions from different isotropic focal activation sources. The contribution of each of the sources was determined by an iterative optimization process modifying the UDL propagation model after comparing the modeled signals against u-EGM signals acquired during epicardial atrial mapping in sinus rhythm (SR) and AF. Finally, the complete activation map was reconstructed by combining individual solutions. Preliminary analysis of this approach has been reported in [21].

2. Materials and methods

2.1. High-density atrial epicardium recordings

The clinical data used in this study was obtained from a 61 years-old male patient with coronary artery disease, without a history of AF which echocardiographic examination revealed a normal left ventricular ejection fraction and normal atrial dimensions. The patient was admitted for open chest surgery at Erasmus Medical Center Rotterdam (Rotterdam, The Netherlands) in whom an intraoperative electrophysiological study was performed. The patient was informed and signed the consent form. During the intervention, a custom made high-density MEA mapping sensor (*Applied Biomedical Systems B.V., Maastricht, The Netherlands*) was positioned on the epicardial wall of the left and right atrium following a sequence of epicardial locations, as illustrated in Fig. 1(a). Datasets of high-density u-EGMs signals were acquired during SR and AF.

The custom MEA sensor measures 3.0×1.4 cm, is composed by 128 circular gold plated electrodes (2 mm inter-electrode distance, 1 mm diameter) organized in an 8×16 rectangular grid. Electrode channels corresponding to each corner of the mapping array were not available for mapping and were reserved for storing surface ECG, reference and calibration signals, resulting in 124 u-EGM signals available for analysis (Fig. 1(b)). The acquired u-EGM signals were band-pass filtered (1–500 Hz) sampled and digitized at 1 kHz. The recording length during SR episodes was 5 s and 10 s during AF episodes.

Automatic LAT detection was performed off-line after the procedure using a wavelet-based algorithm [22] and subsequently audited by an expert electrophysiologist blind to the detection outcome of this work. Therefore, the resulting LATs were considered as *"ground truth"* for performance evaluation of the proposed algorithm.

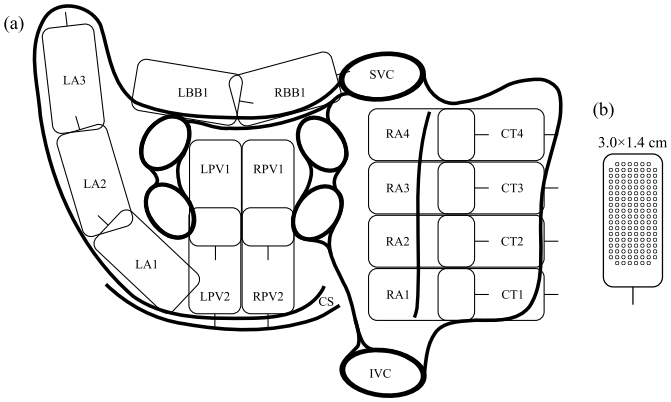

Fig. 1. Schematic of the mapping procedure in posterior view: (a) Anatomical location of the MEA sensor in the atrium and (b) MEA sensor used for mapping procedure. CS: Coronary Sinus, CT: Crista Terminalis, IVC: Inferior Vena Cava, LA: Left Appendage, LBB: Left Bachmann Bundle, LPV: Left Pulmonary Vein, RA: Right Appendage, RBB: Right Bachmann Bundle, RPV: Right Pulmonary Vein, SVC: Superior Vena Cava.

2.2. Algorithm overview and notation

Before algorithm starts, a 100 ms signal excerpt that includes a complete activation across the MEA sensor is selected and the mapping array is segmented in 44 overlapped groups of 5×5 electrodes (area 64 mm^2), being this the size of the analyzing mask in this work. A comprehensive flow of the processing steps is described below:

```
L1: For each 5 × 5 group of electrodes:
     1. Estimate conduction velocity and initial
        focus location, which is considered the
        source for this estimation.
     2. Generate activation pattern and modelled
        u-EGMs.
     3. Compare measured against modelled u-EGMs.
    L2: While the similarity is below a given
        threshold or the maximum number of iter-
        ations is not reached:
        a) Compute new focus location for next
           iteration.
        b) Generate new activation pattern and
           modelled u-EGMs.
        c) Compare measured against modelled
           u-EGM signals.
    End of loop L2.
End of loop L1. Go to step 1 unless all 5 × 5
groups have been already analysed.
4. Activation map reconstruction.
```

For notation, $s_i[n]$ stands for the recorded u-EGM signal corresponding to the ith electrode, $i = 1 \ldots 25$, from the 5×5 group under analysis and $\hat{s}_i[n]$ denotes the modeled u-EGM signal corresponding to the same electrode located in the cardiac tissue model.

2.3. Activation pattern and tissue model

The basic activation pattern can be generalized as a single focal point generating an activation wavefront concentrically spreading