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The Role of Atrial Modeling in the Development of ECG Processing Tools

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Abstract— **The standard ECG remains the most common non-invasive tool for assessing atrial fibrillation. Specific signal processing techniques have been developed to improve the diagnosis. However, validation of such tools is challenging and comprehensive invasive data may not easily be obtained. To facilitate this task, we developed a computer model of the atria. In this electrophysiological model, atrial fibrillation was simulated and the manifestation of its electrical activity on the thorax was computed. The resulting realistic-looking synthetic ECG signals were used as benchmarks for testing, evaluating and comparing ECG processing techniques such as cancellation of the ventricular activity, vectorcardiography and dominant frequency analysis.**

Keywords— **atrial arrhythmia, computer modeling, electrocardiograms, signal processing, validation**

I. Introduction

Atrial fibrillation (AF) is the most frequent rhythm disorder in humans and often leads to severe complications such as heart failure and stroke. Standard electrocardiogram (ECG) is the most common non-invasive tool for diagnosing cardiac arrhythmias. While different etiologies of AF have been identified, their relations to the AF dynamics and to the resulting electrical activity as observed on the torso remain unclear.

Signal processing tools have been developed to automatically analyze electrical signals (electrograms, ECGs) during an arrhythmia, and to extract some information about the progression of the disease [1]. The clinical use of spectral analysis (dominant frequency in particular) to identify potential high frequency sources of AF illustrates the importance of signal processing for catheter ablation therapy [2].

Validating these techniques requires some gold standard. Computer models provide such a standard since the substrate properties, wavelet dynamics and electrical signals can all be monitored. For instance, computer models have been used to demonstrate the correspondence between electrogram maximal derivative and local activation time [3], and to test the validity of estimating the atrial rate from electrograms [2,4,5]. Extending this approach to ECGs enables a direct comparison between invasive and non-invasive diagnosis within a simulation framework.

This paper describes the use of a computer model of the atria to generate realistic synthetic ECG signals to support the development of new ECG processing tools, validate them, and measure their performance. Applications to QRST cancellation and interpretation of spectral analysis and vectorcardiography are presented.

II. Methods

A. Atrial model and simulated ECGs

A three dimensional model of human atria was constructed from magnetic resonance images [1], including holes at sites of the entries and exits of the vessels as well as at the locations of the valves connecting the atria to the ventricles (Fig. 1A). The electrical propagation of the cardiac impulse was simulated using a reaction-diffusion system based on a detailed ionic model of the cell membrane

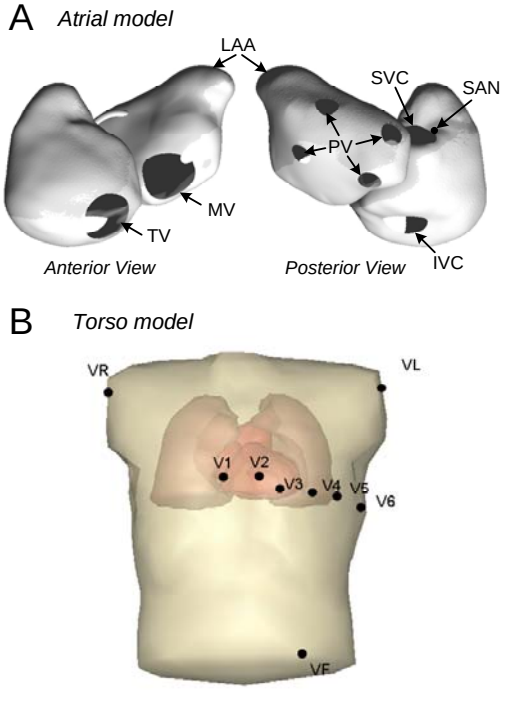

Fig. 1 Geometry of the models representing the atria and the thorax

kinetics [6,7]. Boundary element methods were applied to a compartmental torso model (Fig. 1B) including the atria, the ventricles, blood cavities and the lungs, to compute body surface potentials [8]. This approach has been previously validated for normal rhythm [8].

In order to create a substrate for AF, patchy heterogeneities in action potential duration were introduced by modifying the local membrane properties [9,10]. AF was induced by rapid pacing in the left atrium appendage. Standard 12-lead ECGs were computed during episodes of simulated AF and compared to clinical signals recorded in a patient with chronic AF [11].

The model simulates the atrial contribution to the ECG. The ventricular contribution was extracted from the ECG during (fast) regular rhythm in patients with paroxysmal AF [12]. The sum of these two components formed a complete synthetic ECG.

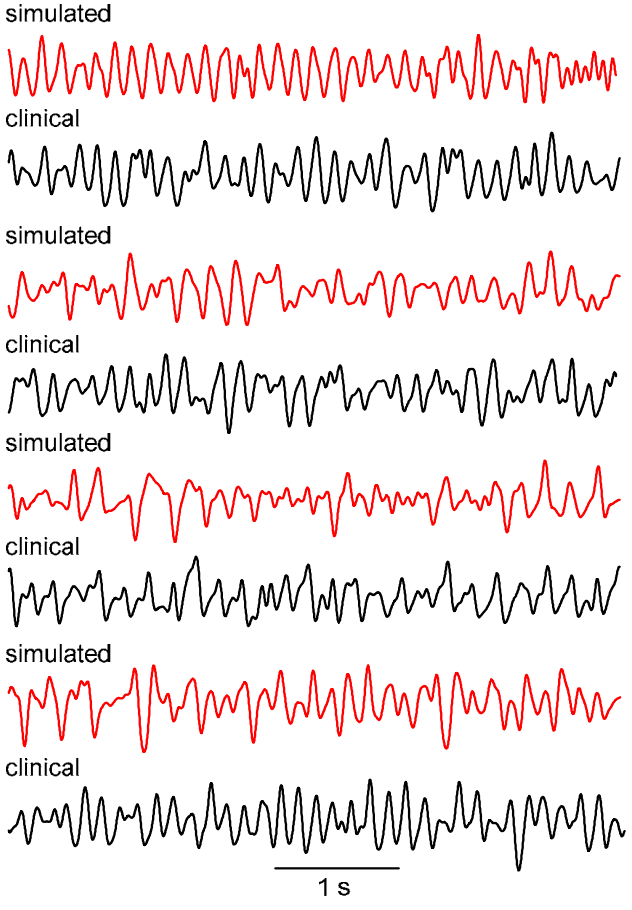

Fig. 2 Examples of simulated and clinical ECGs (after QRST cancellation) recorded on lead V1.

B. Data analysis

A set of signal processing techniques were applied to the simulated ECG signals, namely:

1. Cancellation of the ventricular activity [12];
2. Computation of the equivalent dipole (VCG) from the 12-lead ECG [13];
3. Enhanced spectral analysis using phase-rectified signal averaging [14].

The gold standards provided by the computer model were respectively:

1. The atrial contribution to the ECG;
2. The equivalent dipole ("true dipole") computed by summing the dipole sources located within the myocardium [8,15];
3. The distribution of local atrial rates extracted from the time course of transmembrane potentials.

At each step, the output was compared to the gold standard.

III. Results

Simulated AF was observed as multiple reentrant wave fronts that propagate and interact in a random fashion over the atrial surface [7,9,11]. Figure 2 displays examples of ECGs for different episodes of simulated AF as well as clinical ECGs recorded in different patients. The simulated ECGs showed many of the features of clinical ECGs, both in the time and in the frequency domain.

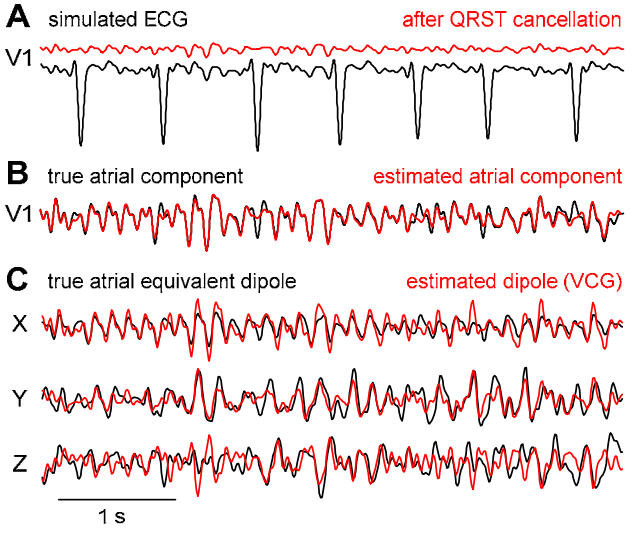

Fig. 3 (A) simulated ECG before and after QRST cancellation; (B) comparison with the true atrial component; (C) estimated dipole and true atrial equivalent dipole.

Figure 3 demonstrates how the processing of ECG signals is tested using the model. First, the ventricular activity was suppressed from the ECG (Fig. 3A). Since the true atrial component was known, the performance of the QRST cancellation algorithm could be measured using root mean square error for instance (Fig. 3B). Then, the equivalent dipole (VCG) of the atria was derived from the atrial component of the 12-lead ECG [15]. The resulting X, Y and Z components were compared with the true atrial equivalent dipole (Fig. 3C).

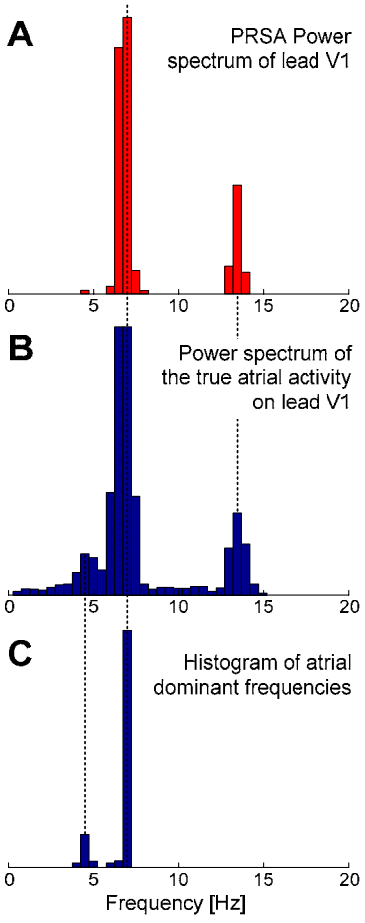

Fig. 4 (A) Power spectrum computed using phase-rectified signal averaging (PRSA) on lead V1 after QRST cancellation. (B) Power spectrum of the atrial contribution to lead V1. (C) Histogram of atrial dominant frequencies computed from the transmembrane potential time course.

Figure 4 illustrates how the relevance of spectral analysis to the estimation of dominant atrial rates can be assessed. The power spectrum computed using phase-rectified signal averaging [14] on lead V1 after QRST cancellation (Fig. 4A) can be compared to the power spectrum of the true atrial activity on lead V1 (Fig. 4B) as well as to the atrial rates measured directly (i.e. invasively) in the myocardium (Fig. 4C). The results show that the basic frequency of AF can be extracted from lead V1 despite the interference of the residual ventricular activity and the presence of harmonics. Phase-rectified signal averaging enhances the dominant frequency, but possibly attenuates the power of secondary basic frequencies that may be associated with secondary AF sources. The analysis of multiple leads or body surface potential maps over the full spectrum can be used to reveal these secondary basic frequencies [16].

IV. Discussion

We have developed a tool to generate synthetic ECG signals similar to those recorded in patients during AF and in which the exact contribution of the atria is available. These signals were found to be appropriate for evaluating, comparing and validating ECG processing algorithms such as QRST cancellation and spectral analysis. In addition, information at the cellular scale about wavelet dynamics, transmembrane potentials and even membrane kinetics are also available. This makes it possible to investigate the link between features of the ECG and underlying tissue properties.

The use of simulated ECG signals permits the development of signal analytical tools through their application to signals that are free of noise, baseline variations and other recording artifacts. Clinical signals are generally more complex than the simulated ones. The morphology of their QRST complexes is more varied than the simulated ones. QRST cancellation is therefore generally more difficult. However, recent advances in preprocessing methods have now attained a sufficient quality [1]. In our simulations, signal duration was limited to 20-30 seconds due to the computational load of detailed electrophysiological models [10], while 5-minute ECG recordings or Holter monitoring are common.

V. Conclusions

Simulated ECGs can be used as synthetic signals for assessing and validating signal processing tools such as QRST cancellation or dominant frequency estimation. Computer models may help select the most valuable features of ECG signals in their relationship with the underlying AF dynamics.

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