Quasi-Periodic Atrial Activity Components in the ECG used to Discriminate between Paroxysmal and Chronic Atrial Fibrillation

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Abstract

Spatiotemporal organization in atrial fibrillation has recently been observed in invasive studies with a left-to-right frequency gradient. We propose the use of a recently developed technique named phase-rectified signal averaging to estimate the mean activation rates in leads V1 and V5 to observe the same left-to-right gradient in a noninvasive manner. Based on these values, a classification procedure between paroxysmal (n=43) and chronic (n=20) atrial fibrillation patient is suggested. The processing steps were: baseline correction and ventricular activity cancellation, followed by the phase-rectified signal averaging technique. The three features used were the dominant frequency values of leads V1 and V5 and the absolute value of the difference between these frequencies. These yielded to 84.1% *of correct classifications (*$p < 8.5 \times 10^{-7}$*).*

1. Introduction

The diagnosis of atrial fibrillation (AF) as such has been based mainly on visual inspection of the surface electrocardiogram (ECG), and limited to establishing its presence or absence [1]. Although there are many substrate abnormalities that may cause AF, they are generally considered as expressing one and the same type of disease. On closer inspection, AF is not a uniform phenomenon. Various degrees of spatiotemporal organization during sustained AF has been observed in animals as well as in humans [2–4].

In 2004, Sorin Lazar *et al.* published results of invasive study [5]. The purpose of the study was to investigate if human AF manifests a left-to-right atrial frequency gradient in the posterior regions of the atria. They observed the presence of higher frequencies at the pulmonary vein/left atrium junction, intermediate in the coronary sinus, and slowest in the posterior right atrium for the paroxysmal AFs. For chronic AFs, the frequencies observed in these regions were uniform.

Many noninvasive (surface ECG) studies have used approaches based on dominant frequency (DF) in order to characterize AF time scales [5–7]. DF is the peak in the spectral estimate of the atrial ECG activity during AF. In noninvasive studies, the DF is generally estimated on lead V1 intervals (typically 5 s long), after ventricular activity cancellation (VAC) while using classical power spectral density (PSD) estimation techniques [7]. The other leads of the standard 12-lead ECG, for which VAC performance is poorer, are generally not considered.

Phase-rectified signal averaging (PRSA) was introduced by Bauer et al. in 2006 [8]. This technique was proposed for the study of quasi-periodic oscillations in noisy, nonstationary signals. It is based on a very simple, intuitively appealing principle, and has been shown to be advantageous over classical power spectral density (PSD) estimation techniques when the perturbation to the quasi-periodic component of interest is $1/f$ noise. This technique has recently been put forward to estimate the atrial activation rate in ECG signals. On realistic simulated ECG signals during AF, the PRSA technique combined with VAC yielded accurate DF estimates. On clinical ECG recordings, it produced DF plausible values [9].

In this paper, we apply the PRSA technique to atrial ECG signals of leads V1 and V5 after applying VAC and take the estimated DFs as representing the mean firing rate of left and right frontal regions of the atria. In doing so, we assume that the surface atrial activity during AF can reasonably be considered as quasi-periodic, at least over a limited time period of 30 seconds. We have study the effectiveness of the estimated DF values to discriminate between paroxysmal and chronic AF patients. First, we present briefly the principle of PRSA and the characteristics of our clinical database. Then we describe our protocol. Further, we present the results on both types of AF and discuss them. The results obtained from the procedure applied to ECG signals are compared to the ones obtained by estimating the DFs after applying only VAC, and the ones obtained from electrograms (Lazar's study). A short conclusion ends this paper.

2. Methods

2.1. A short introduction to PRSA

PRSA, when applied to a signal $\{x_n\}$, helps enhance a possible quasi-periodic component of that signal when it is corrupted by artifacts, non-stationarities and noise. The basic principle of PRSA is the averaging of segments of $\{x_n\}$. These segments are symmetric with respect to so-called anchor points. The anchor points are selected as samples at which the signal instantaneous phase is close to a specific value (typically zero). In this way, the averaging process will enhance the quasi-periodic component of the signal and cancel eventually correlated, non-periodic components (non-stationarities, noise, artifacts, etc).

In the simplest version of PRSA, the anchor points correspond to increases in the signal, i.e. indices n such that

$$x_n > x_{n-1}. \tag{1}$$

Segments of length $2L+1$ centered on the anchor points,

$$x_{n_\nu - L}, x_{n_\nu - L+1}, \ldots, x_{n_\nu + L-2}, x_{n_\nu + L-1} \tag{2}$$

are considered, with $n_\nu, \nu = 1, \ldots, M$ the indices of the anchor points.

Then, all these segments are averaged to obtain the PRSA average $\tilde{x}_k$

$$\tilde{x}_k = \frac{1}{M} \sum_{\nu=1}^{M} x_{n_\nu + k}, k = -L, -L+1, \ldots, L-2, L-1. \tag{3}$$

Finally, a classical PSD estimation technique is applied to $\tilde{x}_k$.

2.2. Clinical signals

The clinical database is composed of 63 30-second standard 12-lead ECG recordings of patients in paroxysmal (n=43) and chronic (n=20) AF. These signals were recorded and stored using a commercial system (Prucka Cardiolab EP system, GE Medical) before radiofrequency catheter ablation. The system used electrocardiographic filtering (0.05 to 150 Hz) and a sampling rate of 1 kHz. In paroxysmal patients (PAF) with sinus rhythm, AF was induced by rapid burst pacing in the coronary sinus or by infusion of isopronol [10].

2.3. Procedure

For all of the AF patients, the 30-second intervals from ECG leads V1 and V5 described below were considered. The following processing steps were applied :

1. Baseline correction as described in [11].
2. VAC using the method described in [11].

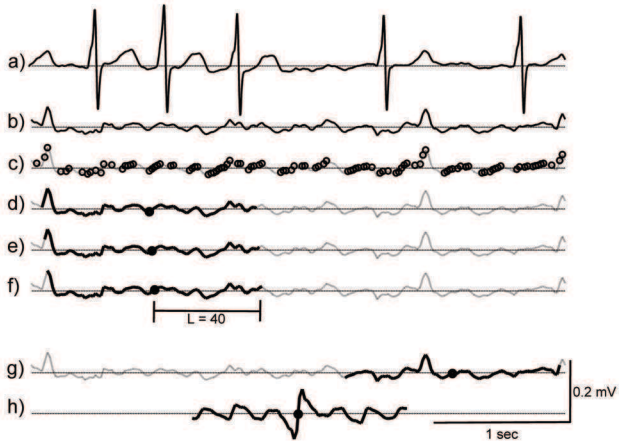

Figure 1. Procedure based on PRSA. (a) Clinical 5-second ECG signal on lead V5 during AF. (b) Estimated atrial activity after applying VAC. (c) Anchor points as described in section 2.1. (d)-(g) Example of segments described in Eq. 2 around the first three and the last anchor points, respectively. (h) PRSA average $\tilde{x}_k$ magnified twenty times, see Eq. 3.

3. Computation of the PRSA average $\tilde{x}_k$ as described in section 2.1.
4. PSD estimation on the PRSA average $\tilde{x}_k$.
5. Identification of the DF estimate as the frequency corresponding to the largest spectral peak.

The steps 1 to 3 of this procedure are illustrated in Fig. 1 on a 5-second ECG signal (lead V5) during AF. Fig. 2 shows two atrial activity PSD estimations obtained after applying only VAC (Fig. 2 a) and after the PRSA-based PSD estimation (Fig. 2 b). These two PSD estimations are obtained from the signals in Fig. 1b and Fig. 1h, respectively. For each clinical feature extraction, the parameter L in Eq. 3 was set to 2,65 sec (2560 samples). The PSD estimates of the PRSA average $\tilde{x}_k$ were smoothed periodograms (Hamming window). The 3 features used for the classification between PAF and CAF patients were the DF values of leads V1 (F_{V1}) and V5 (F_{V5}) and the absolute value of the difference (D) between these frequencies in leads V1 and V5. Based on our observations, a simple classification procedure was used to separate CAF and PAF patients. AF patients with D values lower than $1Hz$ and F_{V1} and F_{V5} values between 6 and $8.5Hz$ were identified as CAF, all others as PAF.

3. Results

The resulting DF values obtained after applying only VAC and after applying the PRSA-based PSD estimation procedure are showed in Fig. 3a and 3b, respectively. After applying only VAC, the CAF patients already exhib-

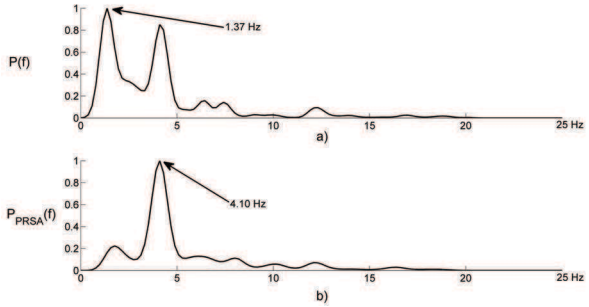

Figure 2. Comparison of (a) the atrial activity PSD estimation after applying VAC (see the signal in Fig. 1b) and (b) the atrial activity PSD estimation after applying the PRSA-based PSD estimation (see the signal in Fig. 1h). The frequency peaks corresponding to the atrial activity DFs are indicated by arrows; the DF value in (a) does not correspond to an atrial activity frequency during AF (between 4 to 10 Hz).

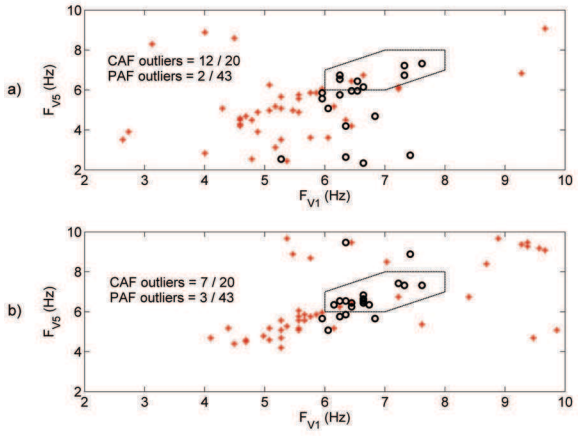

Figure 3. (a) Distribution of the PAF (red crosses) and CAF (black circles) AF patients with respect to their DF values in leads V1 (F_{V1}) and V5 (F_{V5}) obtained after applying VAC only. The region delimited by black lines represents the CAF region. It yielded 77.8% of correct classifications ($p < 3.6 \times 10^{-4}$). (b) Distribution of the PAF (red crosses) and CAF (black circles) AF patients with respect to their DF values in leads V1 (F_{V1}) and V5 (F_{V5}) obtained after applying the PRSA-based procedure. It yielded 84.1% of correct classifications ($p < 8.5 \times 10^{-7}$).

ited DF values between 6 and $8Hz$: $D = 1.3 \pm 1.5$, $F_{V1} = 6.5 \pm 0.6$ and $F_{V5} = 5.4 \pm 1.6$. The PAF patients were characterized by lower DF values: $D = 1.1 \pm 1.3$, $F_{V1} = 5.4 \pm 1.4$ and $F_{V5} = 5.2 \pm 1.6$. The classification criteria mentioned in section 2.3 yielded to 77.8% of correct classifications ($p < 3.6 \times 10^{-4}$).

With the suggested procedure, the CAF patients exhibited similar DF values between 6 and $8Hz$: $D = 0.5 \pm 0.7$, $F_{V1} = 6.6 \pm 0.5$ and $F_{V5} = 6.7 \pm 1.0$. The PAF patients were characterized by two subgroups. Subgroup 1 (n=27) showed similar DF values in leads V1 and V5: $D = 0.3 \pm 0.3$, $F_{V1} = 5.4 \pm 0.7$ and $F_{V5} = 5.3 \pm 0.7$. Subgroup 2 (n=16) revealed dissimilar, higher values: $D = 1.9 \pm 1.7$, $F_{V1} = 8.1 \pm 1.6$ and $F_{V5} = 8.2 \pm 1.7$. The classification criteria mentioned in section 2.3 yielded to 84.1% of correct classifications ($p < 8.5 \times 10^{-7}$).

4. Discussion and conclusions

The present study confirms the presence of left-to-right gradients in some of the AF patients. These were observed after applying only VAC and after applying the procedure based on PRSA. However, the DF estimation after applying only VAC (see Fig. 3a) results in the presence of DF estimates outside the plausibility range (between 4 to 10 Hz). This is especially true in the low-frequency region, VA being responsible for a large spectral peak at the heart rate frequency, typically at 1-2 Hz, and its harmonics.

This study also confirms that left-to-right gradient is preferential in PAF patients. As in Lazar *et al.* study [5], PAF patients incline towards spatial inhomogeneity of the electrical activity in terms of the DF estimate. In comparison, the CAF patients show a leaning towards spatial homogeneity.

In contrast to the invasive studies [5, 12, 13], our results suggest both positive and negative left-to-right gradients. As mentioned in the introduction, the atrial activity observed in leads V1 and V5 represents partial regions of the right and left atria. Figure 4 shows the contribution of the atrial regions with respect to leads V1 (Fig. 4b) and V5 (Fig. 4c). The atrial region contributions are estimated by using a transfer matrix that computes the body surface potentials (corresponding to leads V1 and V5) from the equivalent double layer current source of our atrial computer model [14]. The regions that contribute strongly are represented in red. Those that contribute poorly are represented in blue. It also shows the atrial geometry of the computer model [15]. Note that the regions that contribute the most to leads V1 and V5 represent neither the pulmonary vein regions nor the left atrium junction nor the posterior right atrium region. That is why invasive and noninvasive data are not directly comparable.

Based on these observations, this analysis suggests that the spatial inhomogeneity of the electrical activity during atrial fibrillation observed on the surface electrocardiogram may facilitate the classification of different types of atrial fibrillation in a noninvasive manner.

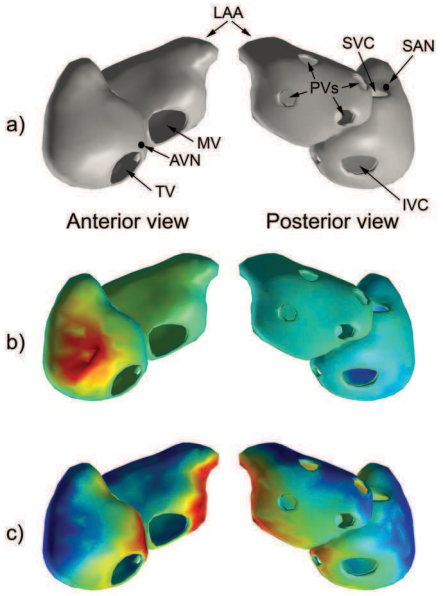

Figure 4. (a) Geometry of the atrial model as seen from an anterior view (left) and a posterior view (right). The major anatomical details shown, including those blocking propagation: the tricuspid valva (TV), the mitral valve (MV), the inferior vena cava (IVC), the superior vena cava (SVC), and the pulmonary veins (PVs). The location of the sinoatrial node (SAN), the atrioventricular node (AVN) and the left atrium appendage (LAA) are indicated. (b) The contribution of the atrial regions to lead V1. The regions that contribute strongly are represented in red. Those that contribute poorly are represented in blue. (c) The contribution of the atrial regions to lead V5.

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