ECG-Based Waveform Characterization of Atrial Fibrillation

M Stridh[1], A Bollmann[2], D Husser[2], L Sörnmo[1]

[1]Dept. of Electrical and Information Technology, Lund University, Sweden, [2] Dept. of Electrophysiology, Heart Center, University Leipzig, Germany.

Abstract

In atrial fibrillation (AF), the body surface signal pattern varies considerably from one patient to another as well as over time. We have developed a new method for ECG-based characterization of AF which explores the morphology of the f-waves. Following QRST cancellation, the method divides the atrial signal into short blocks and performs a model-based analysis of each block. The blocks are then clustered into different waveform patterns. The method was applied to a database of 36 patients (10-s recordings) with organized AF. The results show that the different waveforms in AF are well represented by the proposed model. Each recording was, in average, represented by 3 clusters of which the main cluster covered 31% of the blocks. In lead V1, the typical phase relationship between the fundamental and first harmonic was -82 degrees, indicating sawtooth-like waves with a steeper downslope than upslope.

1. Introduction

Atrial fibrillation (AF) is the most common sustained arrhythmia with a prevalence of 0.4–1% in the general population, progressing to around 8% among those above 80 years of age [1]. The prevalence is expected to become higher as the population grows older. Several treatment options are available for atrial fibrillation, including sinus rhythm conversion, rate control and antiarrhythmic drug therapy, pulmonary vein isolation and surgical procedures. Presently, there are, however, no means to determine the mechanisms of the disease for the individual patient and, as a consequence, no means to predict the outcome of different therapies for the individual patient. The body surface signal pattern of AF varies considerably from one patient to another as well as over time and between leads which has been shown using, e.g., approaches based on time-frequency analysis [2], analysis of the repeatability of individual atrial waves [3] and phase analysis of the ECG [4]. The atrial rate, as measured from the surface ECG, has been shown to be of clinical value for monitoring changes in atrial electrophysiology [5] and for monitoring and predicting antiarrhythmic drug responses [6]. AF with slower rates seems to respond to antiarrhythmic drug therapy [7], while faster rates are more often found in persistent as well as drug- and cardioversion-refractory AF [8].

Several important applications, including matching of ECG patterns to invasive propagation patterns and discrimination between different types of atrial fibrillation patterns, require a characterization approach that can describe the atrial signal pattern with high accuracy. In this paper, we present a new strategy to characterization of AF which clusters a parameter description of the signal into the main signal waveform patterns. The paper is outlined as follows: the proposed method is presented in Sec. 2. A description of the ECG database and the results are presented in Sec. 3. Finally, a discussion of the method and its potential is given in Sec. 4.

2. Methods

The proposed analysis uses residual ECGs resulting from QRST cancellation as its input [9]. Since the spectral content of interest in the residual ECG is well below 50 Hz during atrial arrhythmias, this signal is decimated from 1 kHz to $f_s = 100$ Hz. The decimated residual ECG signal is denoted $x(n)$ where $n = 0, ..., N-1$. The method is comprised of the following steps:

a) *Spectral analysis* for the identification of fundamental (f_0) and harmonic frequencies (f_m). This analysis is also used for evaluation of the spectral structure, e.g., the number of available harmonics and the noise level in the spectrum.

b) *Bandpass filtering* for extraction of the fundamental and harmonic components. The resulting fundamental ($m = 0$) and harmonic components ($m > 0$) are denoted $x_m(n)$ with $n = 0...N-1$. For the purpose of quality control, the part of the power in the spectrum covered by the bandpass filters is calculated.

c) *Parameter estimation* is performed in blocks of 0.5 s duration. For each signal component, one set of estimates of amplitude, $a_{m,p}$, frequency, $f_{m,p}$, and phase, $\phi_{m,p}$, is generated for each block p. The maximum likelihood estimators are given by [10].

$$\hat{f}_{m,p} = \arg\max_{f} \left| \frac{1}{N} \sum_{n=0}^{L-1} x_{m,p}(n) e^{-j2\pi f n} \right|^2 \quad (1)$$

$$\hat{a}_{m,p} = \left| \frac{2}{N} \sum_{n=0}^{L-1} x_{m,p}(n) e^{-j2\pi \hat{f}_{m,p} n} \right| \quad (2)$$

$$\hat{\phi}_{m,p} = \arctan \frac{-\sum_{n=0}^{L-1} x_{m,p}(n)\sin(2\pi \hat{f}_{m,p} n)}{\sum_{n=0}^{L-1} x_{m,p}(n)\cos(2\pi \hat{f}_{m,p} n)} + \frac{\pi}{2} \quad (3)$$

where $x_{m,p}(n) = x_m(n - pL)$ for $n = 0, ..., L-1$ and $-\pi \leq \hat{\phi}_{m,p} \leq \pi$. The term $\frac{\pi}{2}$ is used to convert from cosine to sine phase since sine phase will be used as reference for reconstruction below. The decay of harmonic magnitudes is for each block and harmonic m defined as $\frac{\hat{a}_{m,p}}{\hat{a}_{0,p}}$. Since each block is not perfectly regular, the estimated harmonic frequencies may deviate from their expected positions. Therefore, in order simpilify clustering, each block is modelled as regular by using the expected harmonic frequencies and phase estimates compensated to be valid in the middle of the block ($\phi'_{m,p}$). Reconstruction of the signal is performed based on the blockwise amplitudes, frequencies, and phases of each component. The reconstruction error is evaluated for each block for quality control purposes, see below.

d) *Calculation of phase relationships* based on the compensated phase estimates, $\phi'_{m,p}$, is performed by relating the phase delay of each harmonic to the fundamental phase of that block. In order to compare the phases of the harmonics to that of the fundamental in a meaningful way, the phase estimates need to be converted to a "fundamental" phase scale. In order to convert all phases to such a scale, the following equation is used

$$\phi''_{m,p} = \frac{\phi'_{m,p}}{m} \quad (4)$$

In this way, all phase delays are equivalent to the same time offset. Since the m:th harmonic completes $m+1$ periods when the fundamental completes one period, the m:th harmonic is periodic in 2π in its own phase and in approximately $2\pi/(m+1)$ in fundamental phase scale. The phase relationship between the fundamental and the m:th harmonic is obtained by subtracting $\phi''_{0,p}$ from $\phi''_{m,p}$. Because of the relationship between the periods of the fundamental and its harmonics, the phase relationship of the m:th harmonic must be adjusted with a multiple l of $\frac{2\pi}{m+1}$ to fit into the interval $[-\frac{\pi}{m+1}, \frac{\pi}{m+1}]$ in order to have a unique parameter representation. The selected phase relationship of the m:th harmonic is thus, for block p, given by

$$\theta_{m,p} = \phi''_{m,p} - \phi''_{0,p} \pm l \frac{2\pi}{m+1} \quad (5)$$

e) *Block clustering* The set of the two phase relationships ($\theta_{1,p}$ and $\theta_{2,p}$) for each block is referred to as a phase relationship sample (thus one two-dimensional sample per block). All phase relationship samples are mapped onto a torus geometry where the first harmonic phase relationship spans the large circle of the torus and the second harmonic phase relationship spans the small circle. The torus geometry is chosen because any point on its surface can be described by the two angles and the relation between the two radii can be used to weight deviations in the two phase relationships differently. Before the clustering procedure is initiated, all blocks with too high a model error or too high a deviation between expected and estimated harmonic frequencies, indicating a signal quality problem, are excluded. If all other phase relationships are within the distance d_{max} in the torus geometry, they are averaged to describe the typical waveform morphology of the signal. Averaging is performed separately for each phase relationship by mapping the angles onto the unit circle and evaluating the angle of the average point within the circle. The average over the blocks included in the cluster is denoted $\bar{\theta}_m$. However, the phase relationships are often considerably more spread over the torus, indicating that several groups of waveform morphologies exist. If the spread is larger than d_{max}, a clustering strategy is used to group the samples together to form a number of adequate waveform morphology averages. The selected clustering strategy is an Iterative Minimum-Squared-Error Clustering procedure described in [11] which was adapted to circular averaging.

3. Results

The method was applied to a database of 36 patients (10-s recordings) with AF (combination of baseline, new onset AF, after dofetilide), exhibiting relatively organized activation patterns, i.e., patterns for which harmonics exist. Furthermore, five 1 min recordings were used to evaluate the reproducability of the estimates.

An example of the parametrization procedure of a 10-s residual ECG signal is shown in Fig. 1(a). The corresponding reconstructed signal and model error signals are shown in Figs. 1(b) and 1(c), respectively. In this case, the average energy in the model error was 25% of the average signal energy. Three out of 20 half second blocks were excluded because of a model error larger than 40% or a too large discrepancy between the estimated and expected harmonic positions indicating a very irregular block. The average model error in the entire database was 41% of the original signal energy which was reduced to 22% after exclusion of blocks according to the above criteria.

Clustering of the signal in Fig. 1 is shown in Fig. 2. In this case, the signal is represented with two clusters based on $\bar{\theta}_1$ and $\bar{\theta}_2$ representing 50 and 35% of the blocks, respectively. For each cluster, the average frequency of the

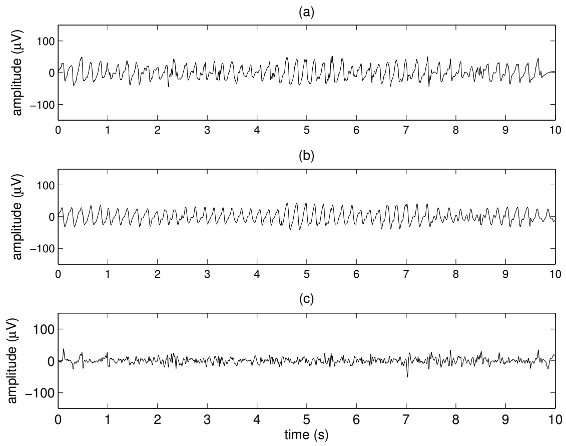

Figure 1. (a) Residual ECG, (b) reconstructed signal from model, and (c) model error.

included blocks is calculated as well as the standard deviation of these frequency estimates (5.2 and 0.29 Hz respectively for cluster 1). Furthermore, the average harmonic magnitude decays, which also contribute to the waveform, of the included blocks are calculated (0.45 and 0.2 respectively for cluster 1). Each recording was, in average, represented by 3 clusters of which the main cluster in average covered 31% of the blocks. The average AF frequency of the main clusters was 5.3 Hz.

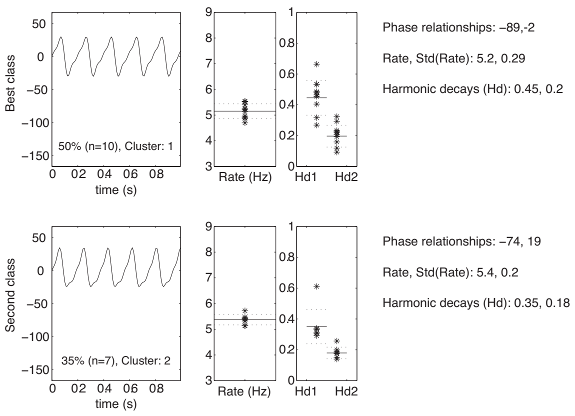

Figure 2. Two main waveform clusters including typical waveform, internal frequency and harmonic decay spread.

The waveform represented by the main cluster is shown for nine patients of the database in Fig. 3. The prevalence of the main cluster is in the range 30-50%. The plotted waveforms are calculated using the average frequency and average harmonic decays of the included blocks.

An overview of how the main clusters are represented in the torus geometry is shown in Fig. 4. In lead V_1, the typical phase relationship between the fundamental and first harmonic was -82 degrees, indicating sawtooth-like waves with a steeper downslope than upslope. Note that most patterns in V_1 have a steeper downslope than upslope which results in a $\bar{\theta}_1$ close to ±90°, i.e., the left side of the torus. The second harmonic phase relationship is more spread between the patients.

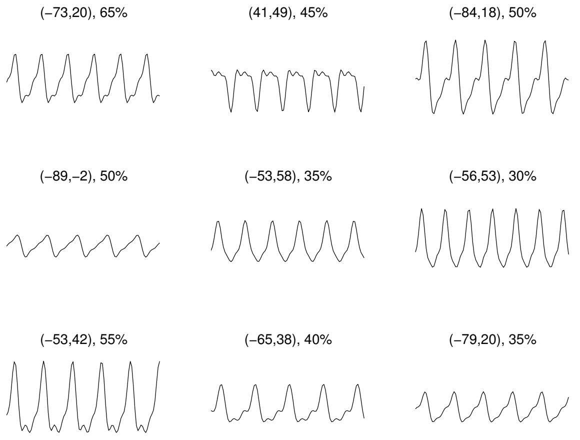

Figure 3. Nine examples of dominant waveform morphology. Above each plot, $\bar{\theta}_1$, $\bar{\theta}_2$, and percentage of blocks represented are displayed.

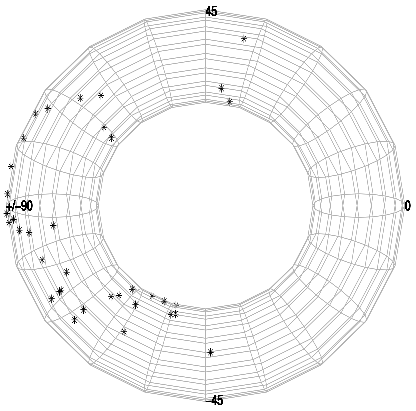

Figure 4. The main clusters for the 36 patients plotted in the torus.

The reproducibility of the method was investigated by analyzing the main waveform cluster of six consecutive 10 s intervals in five 60 second signals. The resulting $\bar{\theta}_1$ (solid) and $\bar{\theta}_2$ (dashed) trends are shown in Fig.5.

4. Discussion and conclusions

In this work, the proposed method is employed for describing the main pattern of a residual ECG. This is an application that requires both parameter estimation and clus-

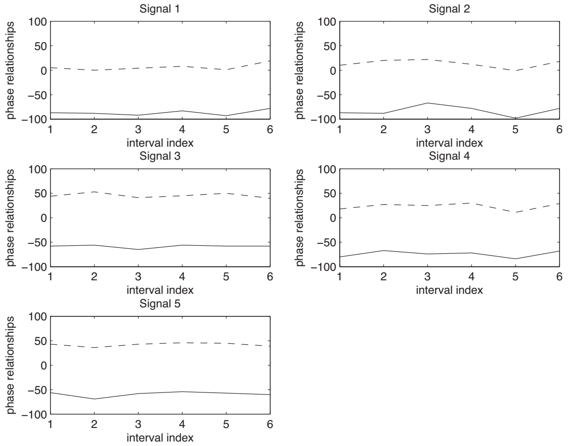

Figure 5. Trends of $\bar{\theta}_1$ and $\bar{\theta}_2$ (solid and dashed respectively) for six consecutive 10 s intervals.

tering. The blockwise parameter estimation can also be used without clustering, e.g., for comparison of simultaneous ECG and invasive activation patterns.

The method is limited to relatively organized AF signals harmonic spectra. Less organized AF signals can be analyzed by the method but will have too low a number of available harmonics. They will thus be described either only by the fundamental or by the fundamental and the first harmonic. The model error will indicate how well the signals are represented.

When summarizing the blockwise descriptions into the overall patterns of the signal, the clustering procedure organizes the phase relationship points in the torus in random order which means that the clusters will be very similar, but not necessarily identical when rerunning the analysis. The waveform represented by the cluster will be very similar since the method employs a limit of the maximum cluster spread in the torus geometry which forces separated phase relationship points into different clusters.

In conclusion, the method has the ability to quantify the waveform of atrial fibrillation signal patterns and can be used to discriminate between different fibrillatory waveform patterns.

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Address for correspondence:

Dr. Martin Stridh
Dept of Electrical and Information Technology, Lund University,
SE-221 00 Lund, Sweden
martin.stridh@eit.lth.se