Full Spectral Analysis of the Atrial Components in the ECG during Atrial Fibrillation

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Abstract

Clinical standard 12-lead ECG recordings over 5 minutes on patients in atrial fibrillation or in atrial flutter were analyzed. After suppression of the signal components related to ventricular activity, the amplitude spectra of all leads were inspected. The spectrum of lead V1 clearly showed the presence of harmonics of a basic frequency, not necessarily at the modal frequency. The dominant basic frequencies in lead V1 of the patients in atrial fibrillation were (mean±SD): 6.04 ± 1.1 Hz, range: [3.5 – 8.8] Hz. For lead V6 the values were: 4.79 ± 1.13 Hz and [3.5–7.7] Hz. In several cases, the spectra suggested the presence of a secondary prominent rhythmic activity. This could be verified by scanning the spectra of all leads for the presence of integer multiples of a different basic frequency. Among the standard 12-leads, leads VR, VL and V6 were the ones in which such multiple, prominent basic frequencies were most frequently identified.

1. Introduction

The modal frequency (MF) observed in the Fourier spectrum of the atrial components in the ECG, usually referred to as the dominant frequency (DF) or peak frequency (PF), is considered to be an estimator of the mean firing rate of the atrial myocytes during atrial fibrillation (AF) [1]. In view of the chaotic nature of AF it seems unlikely that just a single periodicity would be involved.

In a previous study, reported on during last year's meeting [2], atrial signals were simulated by means of a biophysical model of the atria. Self-propagating electrical atrial activity was set up in a realistic, thick-walled 3D model of atrial geometry [3]. Propagation was simulated using a reaction-diffusion system (mono-domain formulation) involving a detailed ionic model of the cell membrane kinetics proposed by Courtemanche *et al* [4].

Different sets of modifications in the normal membrane parameters of the units were introduced, by means of which different types of chaotic atrial activity were simulated [5].

Analysis of the simulated atrial ECGs and the corresponding atrial electrocardiograms (AECG) revealed that the MF need not necessarily correspond to the number of revolutions per second (cps) of any dominant rotor that may be involved in driving AF. Moreover, episodes were observed during which multiple, dominant rotors were present. This suggested that a more complete analysis of spectral detail in the AECG, in particular the search for harmonics of any identified basic frequency (BF), might yield a more complete view on AF complexity. In the current study this concept was tested in its application to clinical data.

2. Methods

2.1. Recorded atrial signals

Standard 12-lead ECG recordings were analyzed, taken from a database of 116 AF patients in sustained AF and from another comprising 16 AFL patients, recorded during routine clinical procedures. The quality of the clinical data permitted a full spectral analysis of the data of 94 AF patients, and of all of the AFL data. The basic demographical details of the AF group are listed in Table 1. The signals were recorded and stored using a commercial,

Table 1. Basic data of the AF patients

	male	female	all
N	45	49	94
age (yr) mean ± SD range	69.5 ± 15 [21 93]	79.2 ±12 [25 95]	74.6 ± 14 [21 95]

clinical ECG recording system (CardioLaptop® AT-110, SCHILLER),which has a dynamic range of ± 10 mV AC (voltage resolution 5 μV) and a sampling rate of 500 sps. The system permits the user to retrieve the raw, digitally

stored data, an option that was emplyed in this study. Filter settings of the system were set at the maximum available bandpass of 0.05 to 150 Hz.

2.2. Signal processing

The ventricular activity (VA), QRST in the ECGs was suppressed by means of a dedicated template matching procedure [6, 7]. The amplitude spectra of all nine signals VR, VL, VF and V1 ... V6 were computed. These constitute a set of common reference signals, the common reference being Wilson's Central Terminal: the mean value of the potentials at the electrodes sensing VR, VL and VF.

The amplitude spectra were computed by means of the discrete Fourier transform (DFT) applied to 10 s episodes. No anti-aliasing filtering was applied. For spectra computed over a period of P seconds the resulting frequency resolution is $1/P$ (Hz), i.e., here 0.1 Hz. In each of the resulting spectra the dominant frequency DF was, in a crude fashion, taken to be the frequency displaying the largest amplitude. Peak values below 3.5 Hz (HR: 210 bpm) were discarded. The spectra shown were normalized to signal power. In addition to the observation of the dominant frequency, a search was carried out for spectral components at integer multiples or rational fractions of these DFs that could be considered as harmonics of the DF, or in the case of rational fractions, identify the DF as a harmonic of spectral components at a lower frequency. Prominent, but less dominant, spectral components that were observed at frequencies other than those mentioned above were taken to be indicative of a secondary prominent periodic atrial activity. Here the presence of, again, spectral components at integer multiples of PF were taken as corroborating this suggestion.

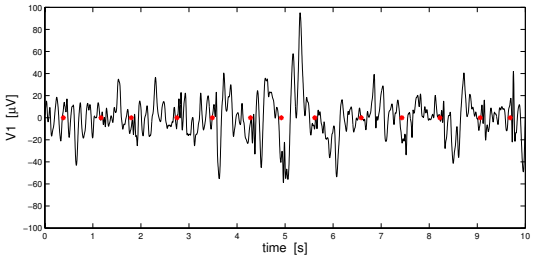

Figure 1. AF signal on lead V1 after QRST suppression. Asterisks mark the timing of onset of the (suppressed) QRS complexes. Mean heart rate over the 10 s episode: 1.129 cps (77.4 bpm).

The mean heart rate (HR) over the individual episodes, expressed in cycles per second (cps), was derived from the untreated 12-lead data, i.e., prior to QRST suppression. Peaks in the AF spectrum at integer multiples of this rate were discarded as candidates for atrial periodicities.

Descriptive statistics are specified by mean $\pm$ SD.

3. Results

3.1. AF data

Although all subsequent 10 s episodes of the 5 minute recordings were analyzed, just the DFs observed in a single episode are documented here. The summary of the observed DF values are presented in Table 2. The values in the lower row of this table mainly reflect the lower limit of 3.5 Hz used in identifying DF values. The single lead that is commonly, with reason considered as providing the optimal view on the electric activity of the atria is lead V1. It is the lead that is most proximal to the atria, in particular to the right atrium. Recent reports in the literature have proposed other leads that may offer additional information [8–10], and possibly provide a clearer view on the electric activity of the left atrium.

In the present study the signals analyzed were restricted to those recorded from the locations of the nine electrodes of the 12-lead system. As outlined in the introduction, we were interested to see if signs of multiple periodicities could be observed in such signals. To this end the spectra were scrutinized for additional signs of periodic activities at frequencies other than the DF.

Clear signs of such additional periodicities were in fact found in 16 of the 94 cases studied. Next to lead V1, the leads that were most indicative were found to be VR, VL and V6.

As an example we show in Fig. 1 the signal of lead V1 after suppression of the QRST involvement. The timing of the onsets of the individual QRS complexes is indicated by asterisks. This facilitates the search for any residual QRST involvement, which, as can be seen, is small.

The amplitude spectrum of the V1 signal, as well as that of lead V6 estimated from the same 10 s episode is shown in Fig. 2. Here, asterisks are shown at integer multiples of the heart rate.

3.2. AFL data

After suppression of the QRST involvement the spectra of atrial signals of the patients in atrial flutter invariably showed a multitude of harmonics of a single frequency. However the basic frequency involved was always equal to the mean heart rate over the 10 s episode involved. Analysis showed that this can be attributed to the close link between atrial and ventricular rhythm. Of the two QRST cancelation methods tested [6], the template matching based variant wiped out the total signal almost completely, the residual mainly reflecting harmonics of the

Table 2. DF values (in Hz) as observed all on all leads over 10 s episodes on N=94 patients.

	VR	VL	VF	V1	V2	V3	V4	V5	V6
mean	5.30	5.64	5.54	6.04	5.08	4.86	4.59	4.71	4.79
SD	1.22	1.29	1.24	1.12	1.24	1.10	1.06	1.08	1.13
max	8.3	9.3	9.6	8.8	8.2	8.8	8.8	7.6	7.7
min	3.5	3.5	3.5	4	3.5	3.5	3.5	3.5	3.5

heart rate. When using the single beat cancelation approach described in [6] the QRST complexes were highly effectively suppressed. For longer RR intervals the main signal components remaining were the flutter wavelets just preceding the subsequent ventricular activity.

4. Discussion and conclusions

Now that high quality QRST cancellation methods have become available, the subsequent analysis of AECG signals is feasible. The example shown in Fig. 1 shows that the involvement of ventricular activity in the "cleaned up" signals is hardly noticeable, as can be appreciate by noting the timing of onset of the (suppressed) QRS complexes. What remains is a highly complex signal, reflecting both biological and instrumentation noise but also some of the complexity of the electrical activity of the chaotic activation of the atrial myocardium.

At present, the spectral analysis of atrial signals receives attention from numerous groups. The results of the present study indicates that the full Fourier spectrum yields more information about the complexity of a particular variant of AF than the analysis of merely its dominant frequency. The same holds true for analyzing the spectra of multiple lead signals rather than using observations from a single lead. Although the DFs observed on the different leads are almost identical (Table. 2), several cases were observed in which at least two major periodic activities were distinguishable. These suggest the presence of two dominant rotors tahat are sufficiently stable over the episode analyzed, each revolving at a different number of revolutions per second, that may drive the entire AF phenomenon. If even more than two prominent rotors are involved, or less stable ones, it remains questionable if these could be identified from the surface ECG.

The methodology used in this study included the inspection of the spectra of multiple leads, while paying due attention to the fact that some of the major peaks observed might reflect mean ventricular rate rather than any atrial activity (with their timing indicated by the asterisks in Fig. 2). In several of the cases studied this led us to discard DFs that could in fact be identified as harmonics of heart rate. Such spectral components, arising from sub-optimal cancelation of QRST involvement, might dominate the spectrum in the absence of other, atrial-related signs of periodic activity.

The analysis presented here was restricted to data recorded from the standard positions of the electrodes of the standard 12-lead system. We are currently involved in the analysis of such data obtained by means of a dedicated optimized electrode montage that also involves just nine electrodes, five of which are a subset of those of the standard 12 leads, the OACG lead system [9]. We expect that the clarity, and accuracy with which multiple DFs can be identified will improve by using this lead system. It includes an electrode on the back at the level opposite lead V1, as was found to be essential.

Subsequent spectral analysis of AFL signals so far has not provided any additional information. A dedicated type of QRST cancelation, if at all possible, needs to be devised.

For diagnostic applications, the signal analytical analysis of the pure AF signals seems to be promising. As shown, the ones involving spectral analysis benefit from a full analysis of the signal spectrum and their application to simultaneously recorded multiple lead signals.

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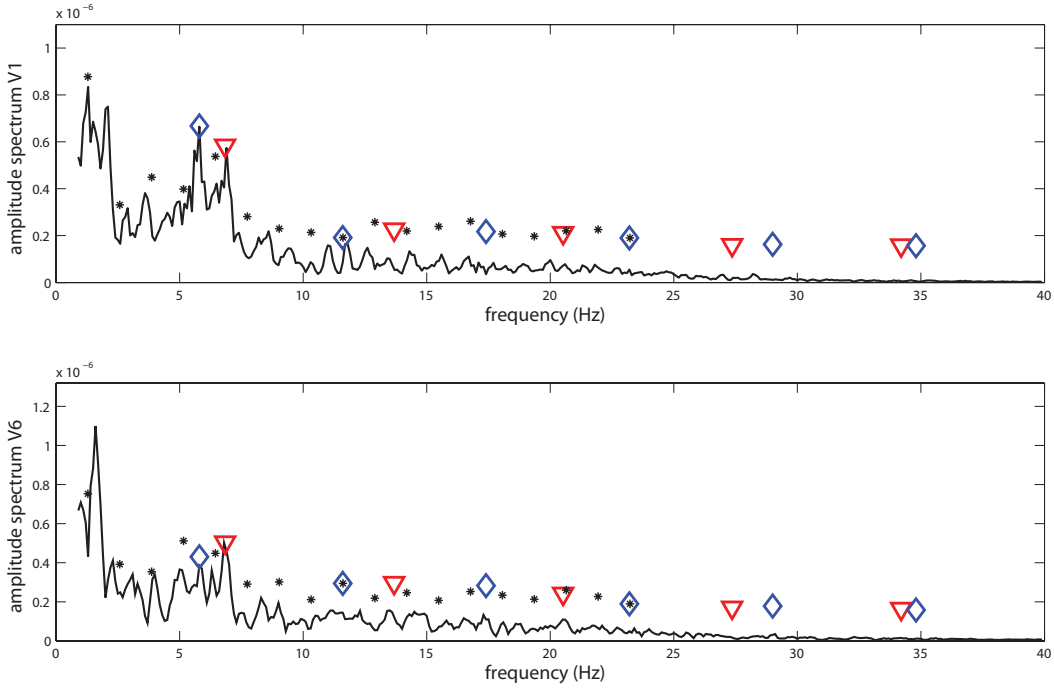

Figure 2. Normalized amplitude spectra of the signals of leads V1 (top) and V6 (bottom). The asterisks indicate multiples of the heart rate, diamonds the dominant BF (5.8 Hz) in lead V1 and some of its harmonics, triangles the dominant BF (6.8 Hz) in V6 and its harmonics.

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