A new approach for frequency analysis of complex fractionated atrial electrograms

Minh Phuong Nguyen, Christopher Schilling and Olaf Dössel

Abstract— **Atrial fibrillation (AFib) is the most common cardiac arrhythmia. Areas in atrial tissue with complex fractionated atrial electrograms (CFAEs) are among others responsible for the maintenance of AFib. Those areas are ideal target sites for ablation to eliminate AFib and restore sinus rhythm. As CFAEs are associated with high fibrillatory frequency, automated identification of CFAEs with spectral analysis helps developing objective strategies for AFib ablation. While the application of current techniques is restricted, this paper introduces a new approach to determine characteristic frequencies during AFib. By using Teager's energy operator we calculate the signal envelope and study its spectrum after Fast Fourier Transformation. Harmonic analysis of distinctive peaks in the power spectrum is carried out to assess characteristic frequencies of a CFAE. While the currently available methods only find one dominant frequency in the spectrum of the signal, our method is capable to find multiple characteristic frequencies, if present. Since it is believed that during AFib the atrium is activated by one or multiple wavelets, our method opens new opportunities for investigation of multiple wavelets propagation.**

Index Terms— **Atrial Fibrillation, CFAEs, Frequency Analysis, Multiple Wavelets**

I. INTRODUCTION

Atrial fibrillation (AFib) is characterized by rapid and uncoordinated atrial contractions inducing an irregular ventricular response. In spite of the extensively studies and accumulating clinical experience, the mechanisms underlying AFib in human are not yet fully understood and therewith approaches in treating AFib and preventing its recurrence are still suboptimal. The most common curative method of AFib is catheter ablation. A number of studies indicate that areas in atrium with complex fractionated atrial electrograms (CFAEs) are responsible for the maintenance of AFib and thus, are to be ablated [1][2][3][4].

Great efforts are made in signal processing to develop algorithms for automated identification of CFAEs. Because of irregular deflections and perturbation of the baseline, time domain processing of CFAEs encounters many difficulties. In contrast frequency analysis offers opportunity to estimate the rate and organization of activation in atrial electrograms. The most common application is the use of "dominant frequency" (DF) analysis [5].

A. Current Method of Dominant Frequency Analysis

The DF analysis examines the power spectrum of the electrogram's envelope. In most literature, the method proposed by Botteron and Smith [6] is used for envelope detection, where the signal undergoes the following steps:

- Bandpass filtering at 40–250 Hz
- Rectification
- Lowpass filtering at 20 Hz.

After the signal envelope is Fourier-transformed, the maximum peak in its power spectrum can be found. The frequency at that maximum peak is defined as the DF.

B. Clinical Usage of the Dominant Frequency

On certain preconditions, the DF obtained with the above mentioned technique can be considered as an estimation of the atrial activation rate. It is suggested that high frequency sources detected with DF analysis may be drivers of the fibrillation and thus, ablation at these sites results in a slowing of the fibrillatory process and a possible termination of AFib [2][5].

Since DF gives the inverse average of AFib cycle length within a timespan, it is only valid for electrograms of high organization [5][7]. This fact bounds the use of DF analysis on signals with a certain periodicity.

C. Aim of this Work

It is hypothesized that the irregular activities of the atrium during AFib are caused by one or multiple wavelets propagating in different directions [8][9]. Atrial electrogram records the electrical activity of the measured site when one wavelet or a superposition of several wavelets with different frequency propagates over it. Because of methodical restriction, DF analysis can examine only the propagation of one wavelet.

We sought for a new approach to exploit the signal spectrum for more information than only one DF. Based on the fact that a periodic signal has the power concentrated at its fundamental frequency and its harmonics, we use harmonic analysis to develop an algorithm finding all fundamental frequencies in a signal where they and their harmonics are superimposed.

II. MATERIALS

Intracardiac electrograms of 8 patients with paroxysmal or persistent AFib were recorded during endocardial mapping at roof, septum, anterior and posterior wall of the left atrium. A Lasso® catheter (Biosense Webster) with 10 electrodes was used. Nine leads of bipolar intracardiac electrograms outlined the potential difference between each two adjacent electrodes. The data was recorded by Ensite NavX® system (St. Jude Medical) with a sample frequency of 1200 Hz. Each

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recording had a length of 5 or 6 seconds. In total we had 6 episodes for each of the 8 patient data sets.

III. Methods

The method can be divided into three main processing steps: envelope detection, Fourier transformation and characteristic frequency analysis.

Since disturbances are present in most electrograms, a preprocessing step is required. Baseline wander is eliminated by a DWT[1]-based approach [10] where frequencies in range of 0–1.17 Hz are removed. High frequency noise is removed from the atrial electrograms by a generalized equiripple lowpass filter. For later application, the filter stopband corner frequency f_{stop} (with an attenuation of -32 dB) is chosen to be one-eighth of the sample frequency or 150 Hz. As frequencies greater than 150 Hz are beyond the physiological frequency range, this restriction does not lead to information loss.

A. Envelope Detection with Teager's Energy Operator

We present a new approach to calculate the envelope of atrial electrogram by using the Non-Linear Energy Operator (NLEO) proposed by Teager and Kaiser [11].

1) Teager's Energy Operator: Teager's NLEO sets out from the point of view that the energy required to generate an oscillating signal is given by the square of the product of the signal amplitude and signal frequency. For the example of a fundamental sinusoidal oscillation let us consider a mass-spring-system. The motion of a mass m suspended by a spring with force constant k is described by the differential equation

$$\ddot{x} + \frac{k}{m}x = 0, \quad (1)$$

which solution is $x(t) = A\cos(\omega t + \Phi)$. A is the amplitude, $\omega = \sqrt{k/m}$ the angular frequency and Φ the arbitrary initial phase of the oscillation. The total energy E of the system is the sum of the potential and the kinetic energy

$$E = \frac{1}{2}kx^2 + \frac{1}{2}m\dot{x}^2 \overset{subst. x}{\longrightarrow} E = \frac{1}{2}m\omega^2 A^2 \propto A^2\omega^2. \quad (2)$$

Teager proposed the NLEO for time-discrete signals as

$$E_n = E[x_n] = x_n^2 - x_{n+1}x_{n-1}. \quad (3)$$

For the time-discrete counterpart $x_n = A\cos(\Omega n + \Phi)$ of $x(t)$, NLEO yields

$$E_n = E[A\cos(\Omega n + \Phi)] = A^2 \sin^2 \Omega, \quad (4)$$

where Ω is the digital frequency in radians/sample and is given by $\Omega = 2\pi f/f_s$. f is the analog frequency and f_s the sample frequency. For small Ω we obtain

$$E_n \approx A^2\Omega^2. \quad (5)$$

With $\Omega < \pi/4$ or $f/f_s < 1/8$ the relative error in the last approximation is always less than 11%. Comparing this result with (2), we see that the output of NLEO can be considered as an indication of the energy of the signal x_n.

[1]Discrete Wavelet Transformation

2) Envelope Detection: The NLEO highlights deflections with high frequency and high amplitude in the signal and yields an approximation of the signal envelope. The condition $f_{max}/f_s < 1/8$ is met in the preprocessing step.

In order to take the width of an individual peak into account, the NLEO's output is lowpass filtered. For this purpose, a gaussian filter is chosen because both – its impulse response and frequency response – are smooth in the range of interest.

In atrial electrograms peaks are usually 10–20 ms wide. Thus, the effective width of the filter impulse response is set to 17 samples, which, in case of a sample frequency of 1200 Hz, corresponds to 14 ms. As in spectral analysis the frequency range of interest is 0–20 Hz [7], the cutoff frequency f_c is set to 24 Hz. The lowpass filtered NLEO's output is shown in Fig. 1(c).

Compared to the common method described in section I-A, the amplitude of envelope detected with NLEO is not proportional to the amplitude of deflection in electrogram. But more importantly, the NLEO suppresses sections where an isoelectric line is expected, so that disturbance of the baseline will not be interpreted as electrical activity. Thus, the envelope calculated with NLEO contains only physiological deflections, which are considerable for further calculation. Fig. 1 draws a comparison between the results of the two methods for envelope detection.

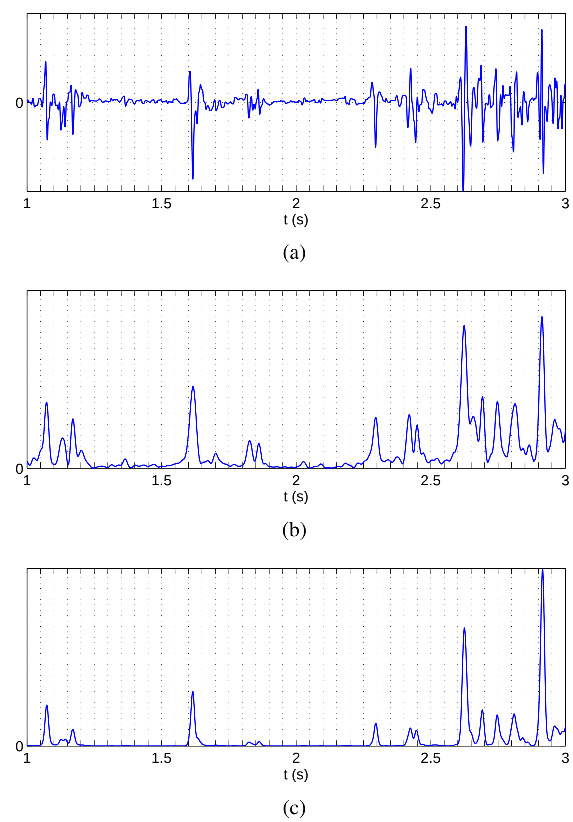

Fig. 1: Envelope of an atrial electrogram (a) calculated with the common method described in section I-A (b) and with NLEO (c).

B. Fast-Fourier-Transformation

The characteristic frequency analysis is performed on the power spectrum of the signal envelope after Fast-Fourier-Transformation (FFT). The optimal length of a signal undergoing FFT for DF analysis is found to be equal 4 s [7]. Signal segments are padded with zeros so that a 8192-point FFT can be carried out. With a sample frequency of 1200 Hz, the frequency resolution of the spectrum is 0.15 Hz.

C. Characteristic Frequencies Analysis

Investigations showed that the power spectrum of the CFAE envelope often presents a dominant peak and its harmonic peaks. The method described in section I-A uses the maximum peak in the spectrum to define the DF. The crucial distinction between the current method and ours is that we consider not only the maximum peak, but all the significant peaks at the fundamental frequencies *and* the existence of their harmonics. Therewith our method is capable to find several characteristic frequencies (CF) of the signal, if present.

The CF analysis is divided into two parts. First, all candidates for CF, which meet the necessary condition of having a significant peak at the fundamental frequency and harmonics, are recorded. They will be then checked on their pathophysiological validity.

As a number of studies proposed that during AFib the atrial activation rate lies between 4 and 9 Hz (240–540 cycles/minute) [5][7], we assume a CF falls within a range of 4–10 Hz. Thus, in order to examine up to at least the third harmonics of a CF, *all local maxima* in the frequency range of 4–30 Hz in the spectrum are recorded with their corresponding frequency. Then an examination on harmonics is carried out on all registered frequencies, which are smaller than 10 Hz. If for a frequency f_1 all its multiple $2f_1$, $3f_1$,... can be found in registered frequencies, then f_1 is a candidate for a CF.

Since CFAE causes a complex power spectrum, there might be frequencies which fulfill the mathematical condition of a CF even though they do not have any physiological relevance. For that reason the following criteria are introduced to remove those irrelevant frequencies:

- There is a global maximum in the spectrum which surely belongs to a CF. Every additional CF must have a peak at its fundamental frequency with a magnitude of at least half the global maximum.
- If the frequency gap between two CFs is smaller than a value Δf, then the one with the smaller peak magnitude will be removed. Δf is an arbitrary parameter and is set to 0.9 Hz (six times of the frequency resolution).
- A CF should not be an integer multiple of another registered CF. Further, if a CF is a multiple of the half of another CF, then one of them has to be discarded. E.g., if $f_2 = 1.5 f_1$ then the second harmonic of f_2 is identical with the third harmonic of f_1. If $|Y(f_2)| < |Y(f_1)|$ then it is eligible to claim that f_2 is not a CF.

D. Organization Index & Energy Density Index

As a higher organized signal generates a spectrum where the power is more concentrated at its fundamental frequency and its harmonics, indices have been proposed to quantify organization as the ratio of the spectrum area under the DF and its multiples divided by the total area [2][7]. Following [7] we define an Organization Index (OI) for a CF f_k as

$$OI_k = \frac{\sum_i \int_{f_{ki}-0.5}^{f_{ki}+0.5} |Y(f)| df}{\int_{3.5}^{30.5} |Y(f)| df}, \tag{6}$$

where $f_{ki} = i \cdot f_k$ with i = 1, 2, 3,... and $f_k \in [4, 10]$. f_{ki} is the i-th harmonic of f_k, whereas $f_{ki} \in [4, 30]$. $|Y(f)|$ is the spectrum of the electrogram's envelope. The areas under the harmonics are calculated over a 1-Hz window. The total area is the integration of the spectrum from 4 Hz to 30 Hz.

In (6) the area in the denominator is constant for every CF of the same signal segment, which is necessary for a comparison between them. For every CF, its OI depends on the area standing in the numerator, which depends on the number of peaks located in the range 4–30 Hz and thus, on the size of CF. This dependence can be reduced when both areas in the numerator and denominator of (6) is divided by the interval, over which they are integrated. Since the area under a harmonic in the spectrum gives the total energy located in the 1-Hz window around that harmonic, the area divided by the integration interval 1-Hz is the average energy density located in that window. Thus, under the same condition and notation as (6) we define the Energy Density Index (EDI) as

$$EDI_k = \frac{\sum_i \int_{f_{ki}-0.5}^{f_{ki}+0.5} |Y(f)| df}{\sum_i 1} \cdot \frac{30.5 - 3.5}{\int_{3.5}^{30.5} |Y(f)| df}. \tag{7}$$

This index gives a ratio of the average energy density concentrated around a CF with its multiples and the average total energy density.

IV. RESULTS & DISCUSSIONS

We proposed a new approach for analyzing characteristic frequencies in CFAEs. This method has been developed on synthetic signals and tested on atrial electrograms, which were recorded from different positions in the left atrium of patients with paroxysmal or persistent AFib.

Our method presents an enhancement of the currently available technique for DF calculation. In case the electrical activation at the measured site is highly organized (Fig. 2), CF analysis of atrial electrogram yields one CF. This result is identical with that of common DF analysis method and represents an estimation of the activation rate in the electrogram. In this case, significant corresponding OI and EDI can be obtained for the one CF.

In most cases of CFAEs, electrical activation seems not to be organized at first glance. But if the propagation of multiple wavelets is underlying these CFAEs, our algorithm is able to outline the individual frequencies of those wavelets. By using Teager's NLEO, disturbance of the baseline is removed

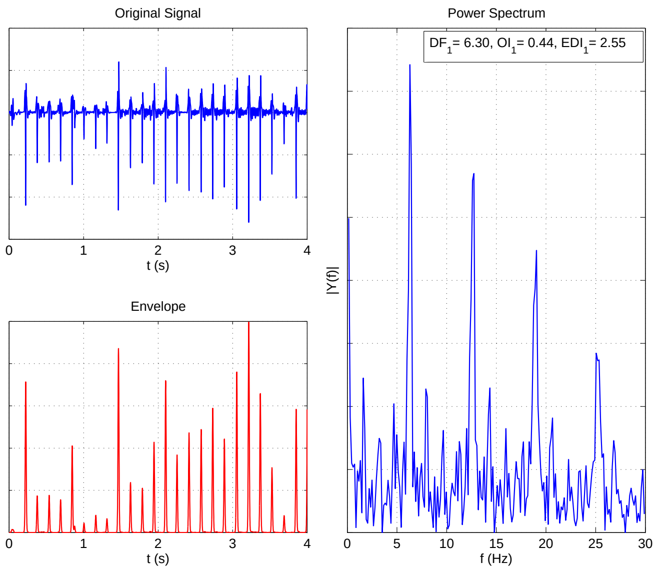

Fig. 2: An organized electrogram with one CF, which is an estimation of the activation rate in the signal.

from the envelope and thus, only physiological deflections are observed in the spectrum.

Fig. 3 shows an irregular CFAE for which the common method would give only a DF at 4.69 Hz, since the maximum of the spectrum in range 4–10 Hz is at 4.69 Hz. The result of our method shows that the original signal is likely to be the superposition of three organized signals with the activation frequency of CF_1, CF_2 and CF_3.

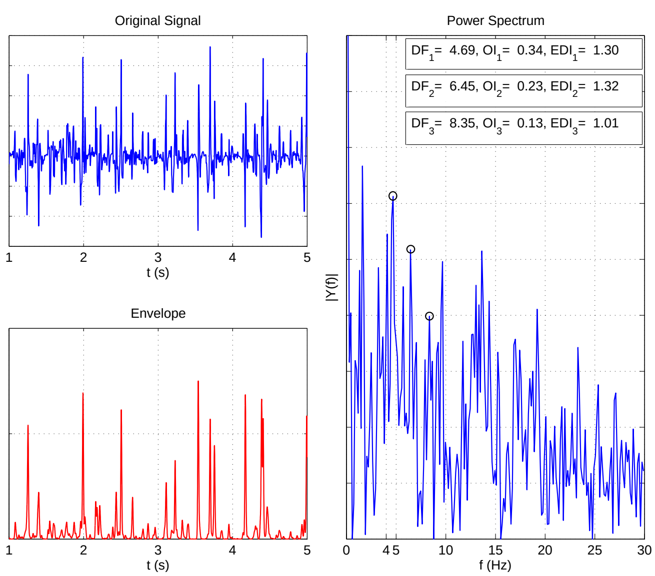

Fig. 3: An unorganized signal with three CFs, where CF_1 and CF_2 are more dominant than CF_3

Furthermore the belonging indices indicate that CF_1 and CF_2 are the two more dominant frequencies. The reason for the sizeable differences between the OIs is the variable numbers of harmonics falling in the observing frequency range 4–30 Hz for each CF. In the calculation of OI_1 the area under five peaks is taken into consideration, while for OI_2 the number of peaks is only four. Whereas the EDI yields for both CFs a plausible quantity: for both CF_1 and CF_2 the average energy density under their harmonics is reasonably greater than the average of energy density within the entire observing frequency range.

V. Conclusions

With the presented approach we provide a new frequency analysis technique which can deal with unorganized CFAEs. Characteristic frequencies of CFAEs can be obtained, which offer a more detailed outline of the signal's underlying organization.

The presence of several CFs indicates the presence of multiple wavelets and thus, our method opens opportunities for investigation of multiple wavelets propagation. Also, with CF analysis the complexity or irregularity of an electrogram can be quantified so that objective assessment of CFAEs can be achieved. With its low computational complexity, this method is capable for real-time application and can be an operator-independent guide for electrophysiologists during catheter ablation.

Beside a slightly different approach to calculate the OI of a CF, we propose the new EDI, which seems to be a suitable quantity for drawing comparison between CFs and for the evaluation of CFs. So far this is a theoretical approach and needs further investigations to warrant its clinical value.

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