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Frequency domain and wavelets applications as methods for ECG signal processing

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1. Introduction

Heart rate is usually defined as the number of heart beats per unit of time. Heart rate variability (HRV) is the measure of variation from one cardiac cycle on the next, utilizing normal morphology.

The analysis of very rapid fluctuations in heart rate (expressed as heart rate variability) is hampered by the fact that the cardiac events are not regularly spaced in time. However, if we are interested in rapid fluctuations theoretically the unit of time mentioned above should be as small as possible. The analysis of fluctuation in heart rate has become increasingly important both in physiological studies and in modeling of the neurocardiovascular system.

It is well known from Fourier theory that a signal can be expressed as the sum of a possibly infinite series of sines and cosines. This sum is also referred to as a Fourier expansion. The big disadvantage of a Fourier however is that it has only frequency resolution and no time resolution. This means that although we might be able to determine all the frequencies present in a signal, we do not know when they are present. The idea behind these time-frequency joint representations is to cut the signal of interest into several parts and then analyze the parts separately. The problem is that cutting the signal corresponds to a convolution between the signal and the cutting window. The wavelet transform or wavelet analysis is probably the most recent solution to overcome the shortcomings of the Fourier transform. In wavelet analysis the use of a fully scalable modulated window solves the signal-cutting problem. The window is shifted along the signal and for every position the spectrum is calculated. Then this process is repeated many times with a slightly shorter (or longer) window for every new cycle. In the end the result will be a collection of time-frequency representations of the signal, all with different resolutions. Because of this collection of representations we can speak of multiresolution analysis. In this case, we normally do not speak about time-frequency representation but about time – scale representations, scale being in a way the opposite of frequency, because the term frequency is reserved for the Fourier transform.The wavelet analysis procedure is to adopt a wavelet prototype function, called an *analyzing wavelet* or *mother wavelet* (figure 1). Temporal analysis is performed with a contracted, high frequency version of the prototype wavelet, while frequency analysis is performed with a dilated, low frequency version of the same wavelet. Because the original signal or function can be represented in times of a wavelet expansion (using coefficients in a linear combination of the wavelet functions), data operations can be performed using just the corresponding wavelet

coefficients. The Fourier transforms utility lies in its ability to analyze a signal in the time domain for its frequency content.

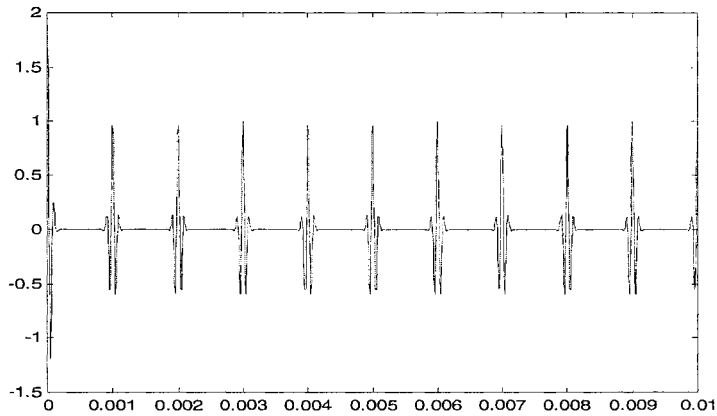

Figure 1: Bioelectrical signal created with Matlab 5.3®

The transform works by first translating a function in the time domain into a function in the frequency domain. The signal can then be analyzed for its frequency content because the Fourier coefficients of the transformed function represent the contribution of each sine and cosine function at each frequency. The fast Fourier transform (FFT) and the discreet wavelet transform (DWT) are both linear operations that generate a data structure that contains log 2n segments of various length, usually filling and transforming it into a different data vector of length 2^n. Within each family of wavelet, are wavelet subclasses distinguished by the number of coefficients and by the level of iteration.

Furthermore, a number of diagnostic applications of this analysis is emanating. such as in the field of acute myocardial infarction, congestive heart failure, sudden cardiac death and diabetic neuropathy, neonatalogy and fetal monitoring. Very often the fluctuations are studied in the frequency domain.

During the past 13 years, the provocative hypothesis by Akselrod et al. that quantitative analysis of fluctuations in hemodynamic parameters is a powerful quantitative means of probing mechanism of short-term cardiovascular control, a new field of impetuous research.

We will therefore discriminate three ranges of the rate of the fluctuations (in terms of average duration of one cycle):

1) Slow variations: few minutes to hours. The heart rate can be defined as twice the number of beats in a 30 seconds time bin.
2) Rapid fluctuations: some tens seconds to a few minutes.
3) Very fast fluctuations: few seconds (or less) to tens seconds.

Detection of a cardiac event series from the ECG is necessary and attention has to be paid to both reliability and accuracy of the QRS detection.

Electrocardiographic assesment of heart rate is necessary. The QRS complexes have to be detected and converted to short pulses.

Consequently, a heart rate variability (HRV) signal is to be derived, which can be subjected to spectral analysis. This is schematically shown in figure 2, where F.T. refers to Fourrier Transform.

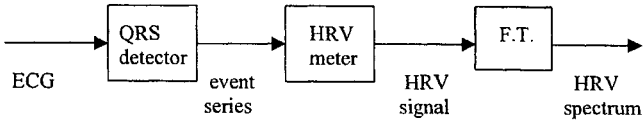

Figure 2: Spectral analysis of rapid fluctuations in heart rate

The wavelets transform or wavelet analysis is probably the most recent solution to overcome the shortcomings of the Fourier transform. In wavelet analysis the use of a fully scalable modulated window solves the signal-cutting problem. The window is shifted along the signal and for every position the spectrum is calculated (figure 3). Then this process is repeated many times with a slightly shorter (or longer) window for every new cycle. In the end the result will be a collection of time-frequency representations of the signal, all with different resolutions. Because of this collection of representations we can speak of a multiresolutions analysis. In the case of wavelets we normally do not speak about time-frequency representations but about time-scale representations, scale being in a way the opposite of frequency, because the term frequency is reserved for the Fourier transform.

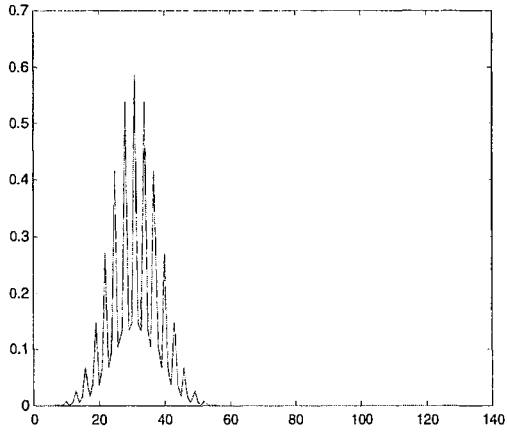

Figure 3: Power spectral density of signal 1 create using the pulstran function

2. Method

To analyze cardiovascular variability signals, power spectrum analysis may be carried out either in nonparametric form (based upon the FFT algorithm) or in parametric form (based upon stochastic black-box modeling).

If heart rate were constant at 72 beats/minute it could easily be described at a frequency of 1.2 Hz. Since heart rate is not truly constant, multiple frequency components comprise its make-up.

The sinus node is highly innervated by the autonomic nervous system. Since the P wave is difficult to detect with precision, an assumption is made that the PR interval remains constant. Measurements are derived from the RR intervals. Successive heart beats are

considered a series of events. Connecting the R to R intervals creates a rhythmic pattern. Via spectral analysis, characteristic frequencies are extracted from the rhythm pattern, coupling them in order of range. In essence, spectral analysis measures the contribution of each of the many frequencies that exist in a given phenomenon (figure 4).

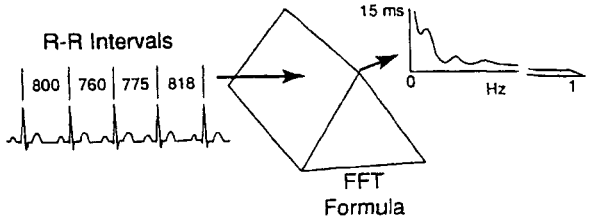

Figure 4: The Fast Fourier Transform (FFT) formula functions like a prism in analyzing heart rate variability.

Since respiration is a rhythmic phenomenon, its measurement can be expressed in frequency.

Example:

10 breaths/minute = 1 breath/6 seconds;
breathing rate 1/6 seconds = 0.17 Hz.

OR

30 breaths/minute = 1 breath per 2 seconds;
breathing rate 1/2 seconds = 0.15 Hz.

Spectral analysis offers the clinician the proportional amount of variation at each component frequency. This may be illustrated by considering how a respiratory rate of 15 breaths/minute affects heart rate variability. The 15 breaths per minute translates to one breath every 4 seconds (1/4 of a respiratory cycle per second) equivalent to 0.25 Hz (cycles/sec) on the frequency spectrum. A spectral peak would be seen at 0.25 Hz. The comparative height of this peak demonstrates its relative contribution to overall heart rate variability. This type of analysis becomes the basis for determining the pathophysiology of heart rate variability (figure 5).

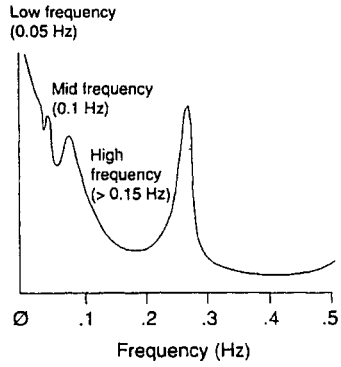

Figure 5: Power spectrum of instantaneous heart rate (HR) fluctuations featuring three main peaks: low-frequency peak (from 0.02 to 0.09 Hz), mid- frequency peak (from 0.09 to 0.15 Hz) and high-frequency peak (around respiratory frequency).

The spectral analysis of beat-by-beat RR interval shows two principal components: Low frequency (LF), component generally centered around 0.05 to 0.15 Hz and whose change in power have been related to the sympathetic activity on the basis of pharmacological and clinical experiments; High frequency (HF), component, in synchrony with the respiration rate (in the range between 0.15 and 0.5 Hz), which considered to be an expresion of the respiration disturbances mediated by the vagal activity (parasympathetic) and are decreased by standing they are mediated solely by the parasympathetic system.

The power related to the LF and HF components is expressed in absolute values as well as in their ratio (LF/HF; so known autonomic index) and the related peak frequencies are useful parameters which help to quantify the sympatho-vagal balance activity.

The Fast Fourier Transform (FFT) accepts as input a time series of data samples (normal to normal coupling intervals) every half a second. The FFT returns a series of amplitudes for sine waves at many discrete frequencies.

The summation of those weighted sine waves would make a time signal that could be sampled to reproduce the original time series of samples, however the FFT output is not a continuos spectrum. The amplitude response from the FFT represents all the frequencies for each of the 128 output bins along the horizontal axis. These amplitudes are in milliseconds. To further explain this consider a time signal which is purely one frequency of variation within the entire sampling window. If the frequency was the center frequency of one of the bins in the FFT output spectrum, the output spectrum would contains zero values for every bin except one. That bin would contain zero-to-peak amplitude of the sinusoidal variation. The range is 0 to 15 ms.

More commonly seen in the literature than amplitude, power spectral density is drawn by squaring each component of the FFT output amplitude spectrum. The squaring function exaggerates the dynamic range, making the smaller amplitude components smaller and the bigger amplitude components bigger.

We have proposed to couple the analysis of HRV to the concept of sympatho-vagal balance. This assumes that the interplay between sympathetic and vagal modulations of sinus node pacemaker activity is organized in a reciprocal fashion, that increased activity in one system is accompanied by decreased activity by the other.

In our study we used two different techniques for analyzing the ECG signal. One was the above-mentioned fast Fourier transform (FFT), on the other way we analyzed the ECG signal also using the wavelet transform. In the early stages of our study we reconstructed the ECG signal from the model of a Gauspuls signal or a Morlet wavelet (figure 6). For this reconstruction we used the commercial available soft (Matlab 5.3®).

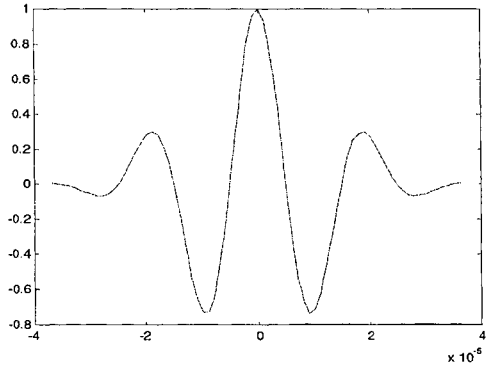

Figure 6: Reconstructed ECG using the MATLAB 5.3® soft

3. Results and disscussion

The study was performed in the Coronary Care Unit of the Cardiology Center Timisoara and data were analyzed in the Computer Department of the County Hospital Timisoara.

Acute myocardial infarction has been shown to result in autonomic imbalance that can be followed by power spectral analysis of the HRV. Power spectral analysis has the potential to quantify sympathetic and parasympathetic nervous system activity.

In our study, data were analyzed using first a ECG devices (PPG-HELLIGE EK 512 P CARDIOGNOST) with 12 leads, that use a "Arrhythmia" analyzer. Data were analyzed as heart rate (in digital form and also as a trend), trend of ventricular premature beats, trend of RR intervals (ms), and also as heart rate variability for short time intervals (10 – 20 minutes) in time domain and frequency domain (figure 7).

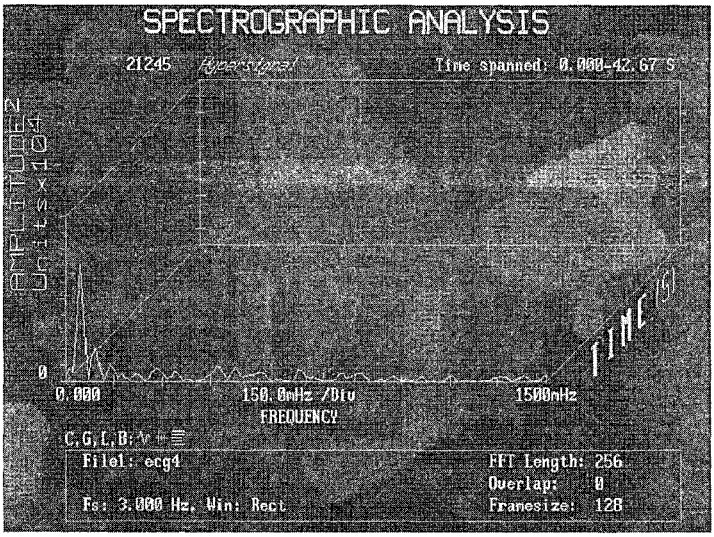

Figure 7: Frequency analysis (FFT) of the ECG signal

We implemented several signal processing techniques: fast Fourier transformation, different types of filters, autocorellation etc. The parameters required for running different processing techniques are established by the program, but the user has the possibility to change them, function on type of the disease and type of the research performed.

We offere to clinical study some features of the ECG spectral analysis in various clinical coditions.

From the large amount of applications of the wavelets, the medical field is from our point of vue, of great interes. Reconstruction of ECG signal and analysis of the ECG signal using DWT offers possibility for furthermore data analysis to understand the mechanisms involved in heart rate variability and late potentials, with application in the management of ventricular arrhythmia.

Limits of the study: Since our study is in an early phase, we need to do a longer research to establish the correlation between late potentials and the DWT of the ECG signal.

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