Proceedings of the 10th Symposium on Biological and Physiological Engineering, Sapporo, Japan, Nov. 30-Dec.2, 1995, pp.477-480

TEMPORAL ASSESSMENT OF CARDIAC RHYTHM FLUCTUATIONS THROUGH WAVELET AND SHORT-TIME FOURIER TRANSFORMS

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Abstract- Heart rate fluctuations contain essential information about the momentary status of various body subsystems, but routine techniques have known difficulties emphasizing and extracting relevant physiological variables. We propose a new test for clinical time-frequency assessment of the heart rate variability (HRV) through multiresolution wavelet transforms and compare with the short-time Fourier analysis. The wavelet decomposition of the HRV is especially appropriate for evaluation of low-frequency cardiac rhythm fluctuations and by functional tests like lying-standing, deep breathing, sustained handgrip and Valsalva manoeuvre. We also investigated localized periodicities and compared temporal patterns of the wavelet-transformed HRV.

Introduction

Computerized assessment of various cardiovascular subsystems is increasing on importance in the last several years. Autonomic control and cardiac responses are studied in order to prevent sudden cardiac death, to cure diabetes and arrhythmias, to reduce influence of genetical deficiencies, stress life conditions or improper nourishment and to increase the success rate of invasive medical interventions.

Cardiac rhythm assessment is essential for correct clinical diagnosis in cardiology [3]. Heart rate fluctuations contain precious information about the current status of various body subsystems, which could be very useful, if extracted properly. By sinus rhythm, the beat is initiated by the autonomic nervous system with its two counteracting subsystems - the sympathetic and parasympathetic nervous system. Increased activity of the sympathetic nervous causes increased heart rate, saliva flow and perspiration. The parasympathetic system operates in opposition to the former, dilating blood vessels and relaxing involuntary smooth muscle fibers. Because control of the autonomic system is carried out by the cerebral cortex, the hypothalamus and the media oblongata. assessment of the heart rate could deliver precious information about bodily subsystems beyond the cardiovascular system and properly channel the attention of the general physician to the origin of pathology.

Proven traditional methods for evaluation of the heart rate variability (HRV) use static spectral estimations of the cardiac rhythm, but lack temporal follow-up capabilities and usually essentially ignore quickly changing events in the signal. We tried to overcome these serious shortcomings through extraction of not only the frequency distributions, but also of the temporal information contents. To accomplish this task we applied the multiresolution wavelet transform (DWT) and the short-time Fourier transform (STFT). We then investigated the behavior of transformed typical and pathological cardiac rhythms under several transform parameters and tuned our choices for physiological relevance. A particularly consequential decision was how to process in time the low- and high-frequency spectral regions to reveal better the underlying control mechanisms. For that purpose we developed several approaches and applied them simultaneously to the results of both wavelet and short-time Fourier transforms.

Methods

In order to cause shifts in the balance between the sympathetic and parasympathetic nervous systems, we simulated functional tests through repetitive lying - standing and sitting - standing experiments. 30 min., 2-channel ECG were digitally recorded at 250 Hz, using the standard Eithoven leads. The experimental subjects were asked to restrict their physical activity, food intake, smoking, etc. before the experiments. The recordings were always carried out at the same time of the day. During the experiment the subject followed a 5 min. sitting - 5 min. standing scheme for an overall duration of 30 minutes.

We analyzed the long-term experimental raw data through ECG wave recognition techniques described earlier [1]. After exclusion of all ectopic beats the original R-R interval series (Fig.1) was linearly interpolated to a new equidistant R-R time series at sampling rate w_s = 5 Hz (assuming that the original R-R interval series approximates closely the true P-P intervals).

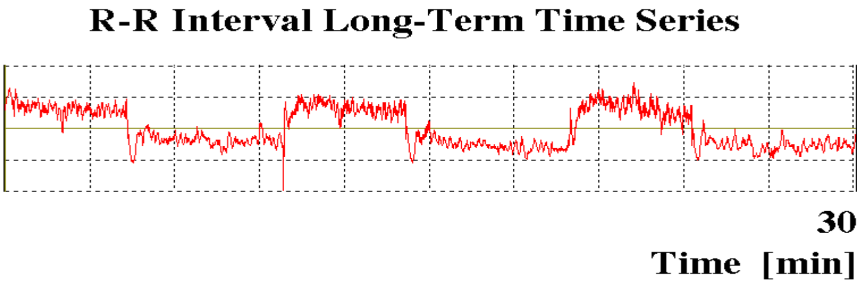

Fig. 1. Original R-R interval variability time series - 5 min. sitting - 5 min.standing functional test. Data is obtained from the ECG by adaptive wave recognition procedures, described elsewhere [1]. After an equidistant time interpolation this series serves as an input to the Short-Time Fourier and to the multiresolution wavelet transforms. Vertical Grid is 100 ms; series overall duration is 30 min.

We performed the standard HRV analysis of the interpolated R-R interval series, mapping the signal into a time-frequency plane (τ, f) through the Short-time Fourier Transform

$$\mathrm{STFT}_\tau f = \int x(t) g^*(t-\tau) e^{-2j\pi f t} dt \ ,$$

where $x(t)$ is the input HRV sequence and $g(t)$ is a window function. The window length was set to the shortest reasonable length (256 points; at overall duration of 8192 points) in order to increase the time resolution (although at the cost of the decreased frequency resolution). The movement step was only 2 points and adjusted to obtain the same number of frequency decompositions over time, as the multiresolution wavelet transform. To perform spectral evaluations we used the following low-frequency (LF) and high-frequency (HF) spectral region limits:

LF: 0.01953 - 0.15 Hz;

HF: 0.15 - 0.5 Hz.

We also analyzed the square moduli (energy) of the multiresolution wavelet transform [2],

$$A_{2^{j-1},l}\, x = \sqrt{2} \sum_k \tilde{h}_{k-2l} A_{2^j,k}\, x$$

$$D_{2^{j-1},l}\, x = \sqrt{2} \sum_k \tilde{g}_{k-2l} A_{2^j,k}\, x ,$$

where $x(t)$ is the input HRV sequence of length $N = 2^J$, decomposed into J multiresolution levels of approximated $A_{2^{-j},l}\, x$ and detail $D_{2^{-j},l}\, x$ signals at time point l, and where $\tilde{g}_k = (-1)^k \tilde{h}_{-k+1}$, required more choices than the STFT. The most important of them was the used type of wavelet. We tested the performance of a number of wavelets (Daubechies, Symlets, Coifman, Battle-Lemarie, Meyer, Optimal-Symmetric, etc.) with various filter lengths. The longer lengths delivered more precision, while the shorter wavelets allowed more compressed feature extraction of the input HRV series and higher computational efficiency. We chose 2 wavelets for further study - the orthogonal Daubechies 9-tap and the Battle-Lemarie 8-tap wavelets.

The time-frequency (time-scale) representation of the signal by the multiresolution wavelet transform splits the frequency space into non-overlapping dyadic blocks

$$[-2^{-j+1}\pi,\ -2^{-j}\pi] \bigcup [2^{-j}\pi,\ 2^{-j+1}\pi]$$

with a constant size on the logarithmic scale. For high frequencies the time resolution grid of the WT becomes better and the frequency resolution - worse, while for low frequencies of f the opposite assertion is valid. Out of 13 available frequency bands of the dyadic DWT decomposition we used the following 7 physiologically relevant ones:

LF: 0.00488-0.00976 Hz, 0.00976-0.01953 Hz, 0.01953-0.03906 Hz, 0.03906-0.07812 Hz, 0.07812-0.15625 Hz;

HF: 0.15625 - 0.3125 Hz, 0.3125 - 0.625 Hz. We analyzed the square moduli (energy) of the dyadic wavelet coefficients $D_{2^{-j}}\, x$ and studied in detail the time courses of the LF:

$$d_{LF}(l) = \sum_j^{LF} (D_{2^{-j},l}\, x)^2 \ ,$$

as well as of the HF, LF+HF band energies and the LF/HF band energy ratio of the wavelet transformed HRV.

Results

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As expected, DWT energy plots (Fig.2, Fig.3) had only a distant resemblance to their corresponding STFT spectral area plots (Fig.4, Fig.5). The Fourier transform showed the typical, well known pattern of the HRV spectra at non-transition parts of the experiment. As expected [4], the LF increased significantly by standing in healthy subjects, but the insufficient frequency resolution of the short quasi-stationary STFT windows offered only limited insight into the LF transition area.

The logarithmic frequency scale of the multiresolution wavelet transform zoomed the slow fluctuations of the cardiac rhythm (LF) in the frequency plane, at the cost of decreased time resolution, when compared to the higher frequency bands.

Wavelet decomposition was able to reveal successfully changes in the HRV and to zoom the LF, however, because of the of the wavelet nature of analyzing kernel (compact support, band filtering properties), test sinus input signals produced modulated time course of the wavelet coefficients.

Fig.2. Daubechies 9-tap multiresolution wavelet Transform of the heart rhythm variability for 30 min.

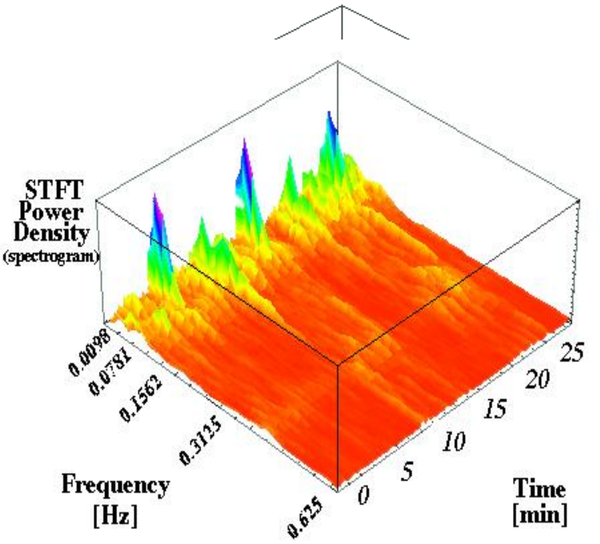
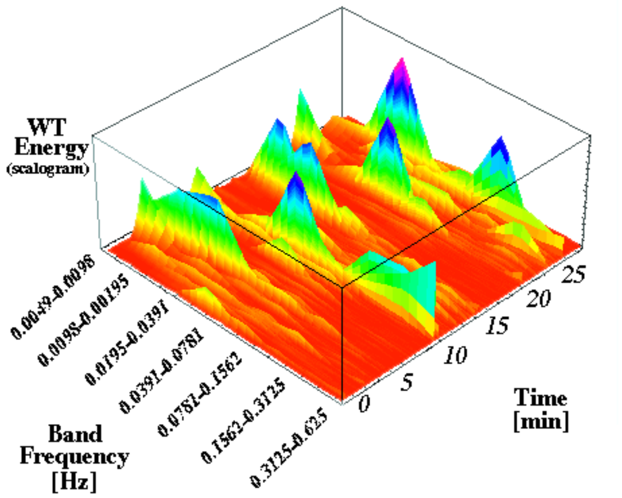


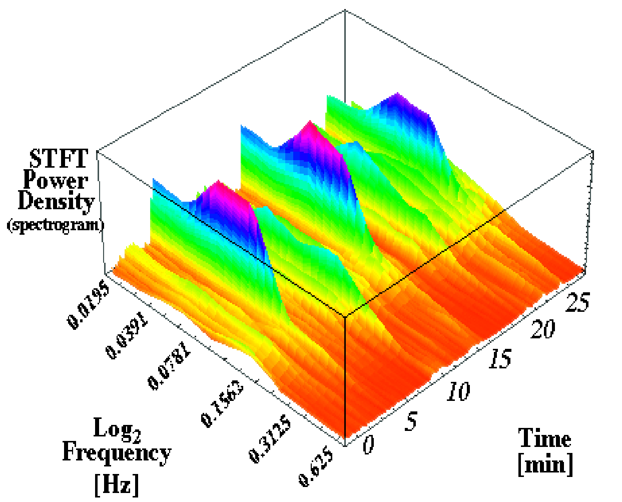
Fig.3. Battle-Lemarie 8-tap multiresolution wavelet



Transform of the heart rhythm variability for 30 min.

Fig.4. Short-Time Fourier Transform of the heart rhythm variability for 30 min.
(Frequency range: 0.01953-0.625 Hz, Hamming window).
Each horizontal curve reflects the stationary frequency distributions of the current data window.

Fig.5. Logarithmic plot of the Short-Time Fourier Transform of the heart rhythm variability for 30 min, comparable with the wavelet transform plots.
(Frequency range: 0.01953-0.625 Hz, Hamming window).
Each horizontal curve reflects the stationary frequency distributions of the current data window.



Battle-Lemarie 8-tap wavelets (Fig.3) produced decompositions with richer information contents about instant shifts of the LF / HF autonomic balance and that made them more difficult to interpret. Daubechies 9-tap filters showed a different, more simple picture of the HRV frequency shifts. Both of them revealed much finer the frequency structure of the slow rhythm variation changes, compared to the STFT (while exhibiting worse performance for fast heart rate changes, usually associated with the respiratory arrhythmia). They showed also generally better time localization of the instantaneous autonomic control shifts, because of the lack of analyzing window, as by the Fourier transform. The difference in resolution is especially evident, if we compare a wavelet decomposition with its corresponding logarithmic spectral array (Fig. 5).

Discussion

Although the Short-Time Fourier Transform is an established method, generally producing exact frequency characterization for stationary signals, functional diagnostic tests typically depend on assessment of non-stationary transient conditions. We show that using STFT even with shortest acceptable window lengths (approx. 50s) for optimal time resolution does not guarantee detection or precise localization of transient events and fast functional changes in the autonomic control, which are still not well understood. At the same time, due to its intrinsic temporal capabilities, the multiresolution wavelet decomposition is able to resolve better the temporal structure of the heart rate variability shifts. Another important advantage of the DWT is its ability to zoom into the low-frequency HRV plane and show logarithmically increasing frequency information in time with decreasing of the frequency. Technical limitations of the traditional spectral methods have not allowed until now a better physiological understanding of the slow fluctuations.

We studied also the autocorrelation sequences of the LF and HF wavelet coefficient energies, as well as of the STFT areas, probing for hidden deterministic oscillatory behavior and testing the degree of randomness in the transformed HRV signal. Further, we used return maps (embedding dimension $m = 2$) in order to identify the presence of possible underlying chaotic drives in the sympathetic and parasympathetic control systems through low- and high-frequency HRV modulations, taking into account the fact, that wavelet coefficients have nonlinear and modulated response in time. The optimal return map lags were determined by nearest maxima of the autocorrelation function for the LF and HF octave band energies. The starting point of these lag searches was moved beyond an initial blanking period to avoid the first peak of the autocorrelation sequence.

We suggest that this new method is particularly well suited for the exact follow-up of the diagnostically important low- and high-frequency variations in the cardiac rhythm during long-term sessions and during standard functional tests (Valsalva manoeuvre, lying to standing test, deep breathing test). The improved identification of underlying cardiac rhythm patterns in healthy and pathological subjects, using the multiresolution wavelet transform in addition to the standard spectral techniques, may prove advantageous for clinical diagnostics and therapeutical decision-making.

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