



Heart Rate Variability Data Simulation with Method of Wavelet Analysis

Galya Georgieva-Tsaneva, Mitko Gospodinov, Evgeniya Gospodinova
Institute of Systems Engineering and Robotics,
Bulgarian Academy of Sciences, Bulgaria

Abstract—A dynamical model based on two Gaussian frequency distributions and Wavelet Transformation is introduced, which is capable of generating realistic synthetic Heart Rate Variability (HRV) series. In the mathematical model is incorporated power spectrum of the real RR tachogram through presentation of the Mayer's wave in the low frequency range and Respiratory Sinus Arrhythmia (RSA) in the high frequency range. The reverse Wavelet Transformation is used in the algorithm for presentation of data from frequency scale into time scale. The development of the presented algorithm is based on the self-similar nature of heart rate variability. The algorithm can be successfully implemented for creation of typical HRV data base, as well as for testing different technologies for biomedical signal processing.

Keywords— Heart Rate Variability; RR interval; synthetic HRV data; wavelet transformation; electrocardiogram.

I. INTRODUCTION

The Heart Rate Variability (HRV) is a measurement of the interaction between sympathetic and parasympathetic activity in autonomic functioning [1], [2]. The health monitoring is important task. The research of HRV is based on the measurement of cardio intervals (RR intervals), drawing of rithmogram, tachogram and following analysis with different mathematical methods. For this aim are detected QRS complexes in the continuous record of electrocardiogram (ECG), estimated the duration of intervals between QRS complexes and finally is calculated the instantaneous heard rate. All processes from detection of cardio complexes to measurement of the duration of cardio intervals are realized by software.

The modeling and analysis of HRV, based on nonlinear transformation, wavelet transformation, geometric methods etc., are subject of an actual research works, published recently [3], [4], [5], [6].

II. HRV DATA

The interval between each consecutive peaks R of one QRS complex defines the duration of cardiological interval. This duration varies even in healthy people. The instantaneous heart rate is the reciprocal value of the RR intervals and it is variable respectively.

On a standard electrocardiogram, the maximum upward deflection of a normal QRS complex is at the peak of the R wave. The duration between two adjacent QRS peaks resulting from sinus node is termed the NN (normal to normal) interval. HRV is the measurement of the variability of the NN intervals. The high variability is an indicator of good health (Fig. 1) The low variability indicates serious risk for pathological diseases (Fig. 2).

There are four frequency areas of HRV [7] shown in Table 1. Two of those are highly important for clinical practice in regards with the study of short cardiological series of 5-10 minutes [8]:

- Low frequency - LF (0.04-0.15 Hz) affects the sympathetic nervous system.
- High frequency - HF (0.15-0.5 Hz) affects the sympathetic and parasympathetic nervous systems [9].

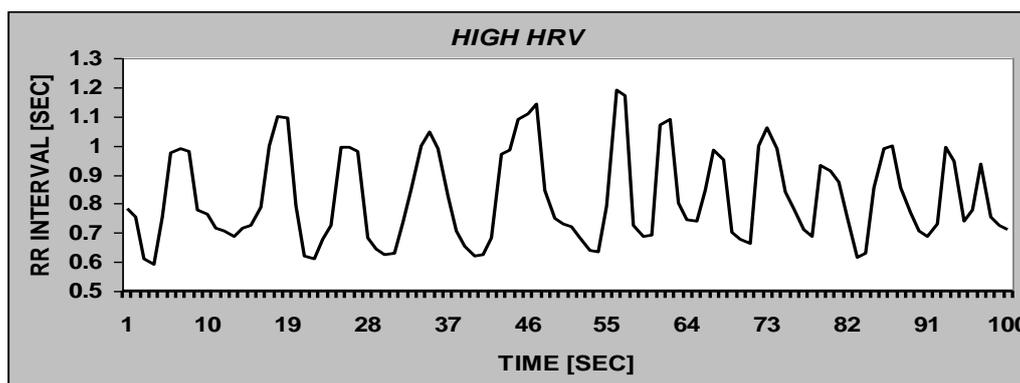


Fig. 1 Normal HRV

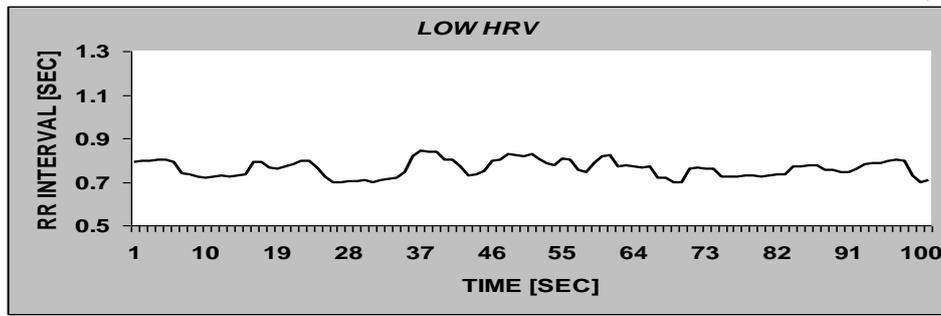


Fig. 2 Abnormal HRV

Sympathetic nervous system is part of autonomic nervous system. Running, fighting, stress may cause the heart rate to reach 180 beats per minute. The other part of autonomic nervous system - parasympathetic nervous system (PNS) – indicates a state of sleep and may reduce heart rate to 60 beats per minute. PNS is coordinated with the respiratory rate, which is known as Respiratory Sinus Arrhythmia (RSA). In case of good health the power spectrum is characterized by two significant peaks in the frequency diagram:

- 0.1 Hz (in LF area) – relevant to the Mayer’s wave due to changes in blood pressure;
- 0.25 Hz (in HF area) – oscillations of the RSA show peaks in the spectrum of HF range, which corresponds to 15 breaths per minute in healthy people.

TABLE I
TYPICAL HRV FREQUENCY BANDS WITH CORRESPONDING RANGE AND CAUSES

Frequency Band	Frequency Range (Hz)	Reason
Total Power (TP)	0-0.5	Variance off all NN intervals
Ultra-low frequency (ULF)	0-0.003	Day/Night Variation
Very low frequency (VLF)	0.003-0.04	Physical Activity
Low frequency (LF)	0.04-0.15	Vagal and Sympathetic Activity
High frequency (HF)	0.15-0.5	Vagal and Respiration Activity
Low/high frequency ratio (LF/HF)	-	Balance between Sympathetic and Parasympathetic Activity

III. WAVELET TRANSFORM

The wavelet transform (WT) is a useful mathematical tool for analyzing the frequency and time components of the signal. The wavelet transforms are based on small waves with limited duration. In discrete wavelet transform (DWT) $S(t)$ signal decomposition on different scales can be present as:

$$S(t) = \text{approx}_N(t) + \sum_{i=1}^N \text{det ail}_i(t) = \sum_j a_s(N, j) \phi_{N,j}(t) + \sum_{i=1}^N \sum_{j=1}^M d_s(i, j) \psi_{i,j}(t). \quad (1)$$

Where:

- $\phi_{N,j}(t)$ - scaling function;
- $\psi_{i,j}(t)$ - wavelet function;
- $a_s(N, j)$ - approx. coefficients;
- $d_s(i, j)$ - detail coefficients.

IV. ALGORITHM FOR SIMULATION OF HRV DATA

The proposed algorithm for simulating of the HRV data represents a modification of the McSharry and Clifford’s algorithm [10]. In the new algorithm Inverse Fourier Transform is replaced by the Inverse Wavelet Transform.

The typical bimodal spectrum of the short sets of Heart Rate Variability data is created by the sum of two Gaussian frequency distributions [10]:

$$S_1(f) = \frac{\sigma_1^2}{\sqrt{2\pi} \cdot c_1^2} \exp\left(-\frac{(f - f_1)^2}{2c_1^2}\right),$$

and

$$S_2(f) = \frac{\sigma_2^2}{\sqrt{2\pi} \cdot c_2^2} \exp\left(-\frac{(f - f_2)^2}{2c_2^2}\right). \quad (2)$$

Where:

- f - frequency;
- f_1 and f_2 - means of frequency;
- c_1 and c_2 - standard deviations;
- σ_1^2 and σ_2^2 - power in the LF and HF bands.

The use of the Gaussian distributions is justified by the typical power spectrum of a real cardio tachogram [10]. The new algorithm for HRV data simulation consists of following steps:

Step 1 – Initialization of the input parameters:

f_1, f_2 - means of frequency, corresponding to Mayer's waves at the LF (Low Frequency) band and RSA at the HF (High Frequency) band;

c_1, c_2 - standard deviations in (2);

N – number of RR generated intervals.

Step 2 – Establishing the frequency sequence of N values $\{f_1, f_2, \dots, f_N\}$, distributed in the interval (0.05, 0.4) Hz. This interval is used in the spectral analysis of the short sets of HRV data.

Step 3 – Generation of frequency complex numbers sequence $\{z_1, z_2, \dots, z_N\}$. The amplitudes are determined by the formula: $|z_i| = \sqrt{S(f_i)}$, where $S(f_i)$ is a summary bimodal power spectrum. The spectrum $S(f_i)$ is obtained by the summation of $S_1(f_i)$ and $S_2(f_i)$ by (2). The phases of complex numbers are generated by random distribution in the interval $(0, 2\pi)$.

Step 4 – Calculation of the Inverse Wavelet Transformation of the generated complex frequency sequence $\{z_1, z_2, \dots, z_N\}$ (using the wavelet Daubechies basis). This generates a complex time series $\{t_1, t_2, \dots, t_N\}$ corresponding to the frequency series.

Step 5 – Multiply the values (resulting time series) by appropriate scaling factors and offset constants added to obtain the specified means of frequency and standard deviations.

The Advantages of the proposed algorithm are:

- The inverse wavelet transformation significantly reduces the otherwise large number of calculations encountered by applying the inverse Fourier transforms. As a result, the CPU time for generation of RR consequences is much lower.
- Daubechies wavelet transform results in a better resolution in both the time and frequency domains, while the Fourier transformation results in a better resolution only in the frequency domain.

V. SIMULATION RESULTS

For investigation and evaluation of HRV series, spectral analysis of the data is performed. By definition, the rithmogram is a graphic diagram showing the dependence of RR intervals as a function of the time. Each vertical bar in the rithmogram indicates the time of the corresponding RR interval. The duration varies from cycle to cycle and therefore reflects the regulatory activity of the nervous system on cardiac activity.

The time series of RR intervals can be represented by RR tachogram, showing variation of cardiac intervals in the time. Different people have different tachogram structures.

On Fig. 3 is shown RR tachogram of a simulated HRV series based on the described algorithm (program realization of Visual C++). The mean RR interval is approximately 1 second and duration of the cardiac interval varies between 0.8 and 1.2 sec. Fig. 4 presents the change of the instantaneous heart rate as function of time, with an average 60 beats/min and standard deviation 5 beat/min. Fig. 5 shows the power spectrum from RR tachogram, derived from five-minutes HRV series, and calculated using the Lomb periodogram [11]. The resulting power spectrum, which reflects the influence of the Mayer's wave and RSA, has distinct peaks in the low frequency area (around 0.1 Hz) and in the high frequency area (around 0.25 Hz).

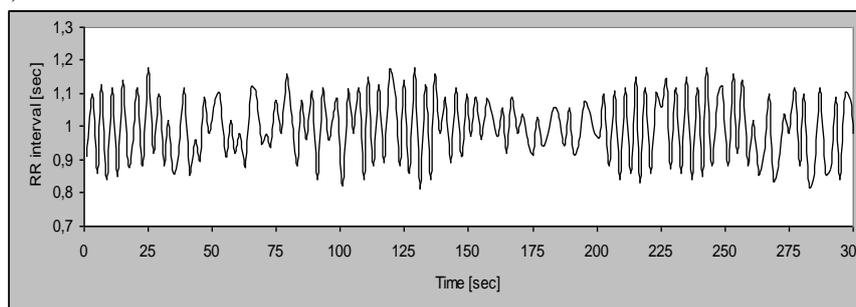


Fig. 3. RR tachogram of HRV series generated

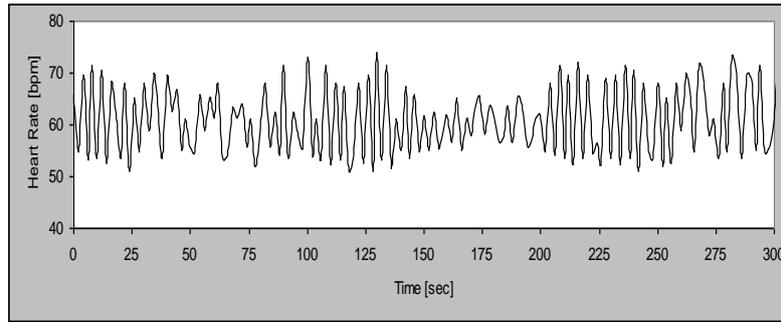


Fig. 4. Instantaneous Heart Rate with mean heart rate 60 bpm and standard deviation 5 bmp

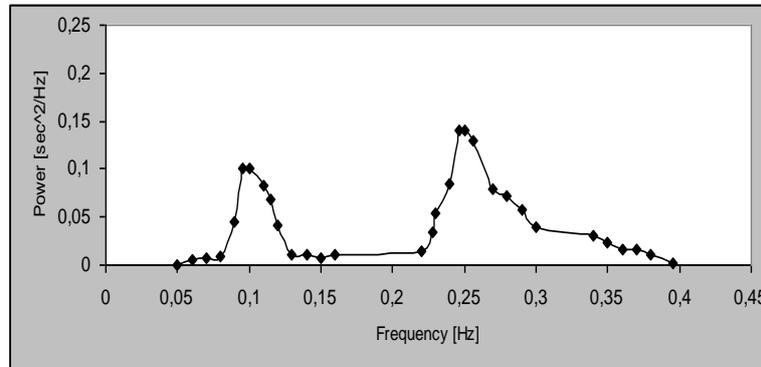


Fig. 5. Power spectrum of the short sets five minute HRV series obtained with Lomb periodogram

The algorithm is analyzed by creating a different number of RR-intervals and by different wavelet bases (Haar and Daubechies with 4, 6, 8, 10, 12 and 20 coefficients). The obtained results show that the test wavelet bases are suitable for generating a time series. The results show that with orthogonal wavelet Daubechies basis (Db2, Db4, Db6, Db8, Db10, Db12 and Db20) is given different percentage zeros. These values obtained by averaging the 200 generated series are shown in Table II.

Table II
THE RESULTS OF STUDIES WITH DIFFERENT BASIS

Number of coefficients	Db2	Db4	Db8	Db10	Db12	Db20
Percentage of zeros (%)	1.56	3.12	12.10	14.84	18.35	28.9

The high percentage of zeros indicates equal durations of the large number of consecutive cardiac cycles, indicating a rhythmic heartbeat. Choosing a different basis (with 2, 4, 8, 10, 12, 20 coefficients) allows to simulate different types of heartbeat according to specific clinical trials.

The results of the comparison between the original algorithm and the modified algorithm in terms of CPU time are given in Table 3 and Table 4. The results in Table 4 were obtained with a wavelet Daubechies basis with 8 coefficients and fourth level of decomposition.

For the implementation of the algorithms based on the Fourier Transform and Wavelet Transform, Visual C++ program code has been written to obtain the displayed results, tables and figures in the paper. The research on Wavelet Transform was conducted on different wavelet Daubechies bases. Significant differences in performance when using different wavelet bases not found. The described studies were performed with processor Pentium IV, 1.50 GHz, 512 MB RAM.

TABLE III
CPU TIME TO SIMULATE HRV DATA BY FOURIER TRANSFORM

Length of series	256 1 series	512 2 series	1024 3 series	2048 4 series	4096 5 series
CPU time (sec.)	0.016	0.078	0.437	1.719	7.516

TABLE IV
CPU TIME TO SIMULATE HRV DATA BY DAUBECHIES TRANSFORM

Length of series	256 1 series	512 2 series	1024 3 series	2048 4 series	4096 5 series
CPU time (sec.)	0.00	0.032	0.032	0.093	0.188

The Areas of application of the proposed algorithm are following:

- The synthetic HRV series could be used to assess the effectiveness of different processing techniques, to analyze and compress biomedical signals.
- The synthetic RR series can be used to understand the theoretical mechanisms of arrhythmia and heart rate variability. The power spectrum of HRV (by Lomb periodogram and FFT) can be investigated.
- A database of realistic simulated HRV series could be created. The database can be uploaded into the public domain and be available for use with the research and educational goals.
- This realistic HRV database could be employed for statistical biomedical hypothesis testing.

VI. CONCLUSION

In the article, a new model, based on a modification of the original McSharry model, which produces RR-intervals, is developed. Effects of the activity of the sympathetic and parasympathetic nervous system are incorporated by generating significant points in the power spectrum of HRV. The new model takes into account the effects of both the Mayer waves and the RSA in the power spectrum of the RR intervals. The benefit to the proposed algorithm is that the simulated cardio logical intervals are in both frequency and time domain, which contributes to more accurately and efficiently modeling of the cardiovascular processes. The CPU time for generation of RR consequences is greatly reduced, leading to decrease in the time needed for computer simulation technology for modeling processes of the heart.

ACKNOWLEDGMENT

This research was carried out as part of the project “Improving the efficiency and quality of education and research potential in the field of system-engineering and robotics” № BG051PO001-3.3.06-0002, founded by European Science Fund.

REFERENCES

- [1] Heart rate variability. *Standards of measurement, physiological interpretation, and clinical use. European Heart Journal*, Vol. 17, Issue 3, 1996, pp.354-381.
- [2] Acharya U.R. , K.P. Joseph, N.Kannathal, C.M. Lim, J.S. Suri. *Heart rate variability: a review. Med. Bio. Eng. Comput*, Vol. 44, Issue 12, 2006, pp.1031-1051.
- [3] Wang Y., S. Lu. *A bounded random process model and its application in heart rate variability analysis. International journal of the Physical Sciences*, Vol. 6 No. 4, 2011, pp.651-659.
- [4] McLernon D.C., N.J. Dabanloo, A. Ayatollahi, V.J. Majd, H.Zhang. *A new nonlinear model for generating RR tachograms. Computer in Cardiology*, Vol.31, 2004, pp.481-484.
- [5] Sztajzel J. *Heart rate variability: a noninvasive electrocardiographic method to measure the autonomic nervous system. Swiss Medical Weekly*, 134 (35-36), 2004, pp. 514-522.
- [6] Batzel J., F.Kappel. *Survey of research in modeling the human respiratory and cardiovascular systems. Research Direction in Distributed Parameter Systems, SIAM Series: Frontiers in applied Mathematics*, Philadelphia, 2003.
- [7] Holland A., M. Aboy. *A novel recursive Fourier transform for nonuniform sampled signals: application to heart rate variability spectrum estimation. Medical & Biological Engineering & Computing*, Vol. 47, No 7, 2009, pp. 697-707.
- [8] Clifford G., F. Azuaje, P. McSharry. *Advanced Methods and Tools for ECG Data Analysis*. Artech House, 2006.
- [9] Clifford G., L. Tarassenko. *Quantifying errors in spectral estimates of HRV due to beat replacement and resampling. Journal of Biomedical Engineering IEEE Trans*, Vol. 52, No 4, 2004, pp. 630-638.
- [10] McSharry P.E., G. Clifford, L. Tarassenko, L.A. Smith. *A dynamical model for generating synthetic electrocardiogram signals. IEEE Trans. Biomed. Eng.*, Vol.50, No 3, 2003, pp.289-294.
- [11] Laguna P., G.B.Moody, R.G.Mark. *Power spectral density of unevenly sampled data by least-square analysis: performance and application to heart rate signals. IEEE Trans. Biomed.Eng.*, Vol. 45, No 6, 1998, pp.698-715. Ivanov, P., Z. Chen, K. Hu, H. Stanley, *Multiscale aspects of cardiac control. Physica A* 344 (3-4), 2004, pp 685-704.