3rd International Conference on Applied Research in
ENGINEERING, SCIENCE AND TECHNOLOGY
20 - 22 NOVEMBER, 2020 PARIS, FRANCE

Evaluation of Time- and Frequency-Domain Features of Ecg Signals

Evgeniya Gospodinova[1,*], Galya Georgieva-Tsaneva[1], Mitko Gospodinov[1], Diana Dimitrova[2]

[1]*Institute of Robotics, Bulgarian Academy of Sciences, Bulgaria*

[2]*Medical University "Prof. Dr. P. Stoyanov", Varna, Branch V. Tarnovo, Bulgaria*

Abstract.

Heart rate variability (HRV) is one of the most studied, informative, non-invasive, easily applicable and promising methods for analysing and evaluating the state of the autonomic nervous system. This method is based on the study of the RR intervals obtained from digital ECG signals. The purpose of the article is to show the results of the study of two groups of subjects: 21 controls and 21 patients with arrhythmia by applying Time-Domain and Frequency-Domain methods. The Time-Domain method includes statistical and geometrical measurements. Statistical measurements use two types of variables to evaluate the data examined. The first type of variables is related to the duration of normal RR intervals (SDNN, SDANN and SDNN index) and the second type of variables is related to the difference in the duration of the adjacent RR intervals (NN50, pNN50, RMSSD). Geometric measurements (HRVTi, TINN) allow a graphical representation of the distribution of RR intervals. These measurements are less affected by the quality of the recorded data and can be considered as an alternative to the statistical parameters. The frequency domain analysis shows the periodic oscillations of the RR series in the context of different frequencies and was performed using the following two methods: Fast Fourier Transform (FFT) and the autoregressive (AR) method. The results obtained show that there are significant statistical differences between the study groups and HRV is decreased in the patients with arrhythmia. Time-Domain and Frequency-Domain methods are standardized, with the limits of norm-pathology being known, making they the preferred.

Keywords: Heart Rate Variability, Time-Domain analysis, Frequency-Domain analysis, ECG signal.

1. Introduction

The use of electrocardiographic (ECG) data for cardiac analysis is a widely used method. The ECG test is a non-invasive test, which provides valuable information about the condition of the cardiovascular system. The essence of this method is to record the electrical potentials that occur during the heart. The presentation of heart rhythm in the form of a dynamic series of intervals between heart attacks and the mathematical analysis of heart rate variability (HRV) is recognized as one of the most informative and non-invasive methods for assessing

the functional state of the human body [4]. Heart rate reflects not only the cardiovascular system but the whole body as it is a major marker of the functioning of the autonomic nervous system [2]. The methods used to analyse HRV are divided into the following two groups: linear and nonlinear methods. Linear methods include: Time-Domain analysis and Frequency-Domain analysis. These two methods are standardized and can be used in clinical practice according to the recommendations described in the standard [1]. A number of authors believe that the information contained in heart rate variability cannot be fully evaluated using only one analysis technique. The existence of specific oscillation intervals for RR series determines the need to use different mathematical approaches in the analysis and evaluation of HRV.

The purpose of this article is to investigate two groups of subjects: healthy controls and patients with heart disease (arrhythmia) through the application of Time-Domain analysis and Frequency-Domain analysis using proprietary software developed by Matlab.

2. Methods for HRV analysis

2.1 Time-Domain Analysis

Time-domain analysis of the HRV is based on the statistical analysis of changes in the duration of consecutive normal NN (RR) intervals obtained from ECG signals. This type of analysis is performed for long records (24 hours) through statistical calculations and graphical measurements [3]. The statistical analysis calculates the following parameters [1]:

- SDNN (ms) – calculates the standard deviation from the average duration of RR intervals over the entire study period. It is used to evaluate total HRV and especially its parasympathetic component. The longer the study lasts, the more total HRV accumulates, so it is necessary that the compared signals have the same duration;
- SDANN (ms) – determines the standard deviation from the average length of RR intervals by calculating 5 minute segments. The registration period is split when using a 24-hour ECG recording (used to evaluate low frequency HRV components);
- SDNN index – determines the average of standard deviations from the average duration of RR intervals for all 5-minute periods divided by the observation period;
- RMSSD (ms) – determines the root mean square of the successive differences of adjacent RR intervals. This parameter reflects the fast, frequency HRV changes;
- NN50 – the number of the pairs of consecutive NN intervals differing by more than 50 ms obtained over the entire recording period;
- pNN50- the percentage of the consecutive intervals that differ by more than 50 ms. Due to the fact that this parameter is determined by adjacent intervals, it reflects the fast and high frequency HRV changes.

The Time-Domain analysis parameters are integral to the sample and describe the average statistical characteristics of the digital performance of the entire signal or fragments thereof. The values of the statistical parameters depend on the length of the data examined and on what hours of the day and under what conditions the ECG records were made [8].

The mathematical analysis of cardiac rhythm allows not only the values of HRV statistics to be determined, but also presented graphically [5, 6].

The geometric methods include the histograms. They allow a figurative representation of the distribution of RR interval series. Geometric methods are less affected by the quality of

the recorded data and can be considered as an alternative to statistical measurements. By plotting the RR histogram, the following parameters are also calculated::

- TINN - the distribution of RR intervals is approximated to a triangle and its base is measured in milliseconds;
- HRV triangular index - a histogram of RR intervals at 7.8125 ms (1/128 sec) is plotted. The total number of RR intervals is divided by the peak height of the histogram. This index reflects total VHF and is directly proportional to parasympathetic activity.

The considered parameters for Time-Domain analysis are highly correlated with each other, which is why the standard [1] proposes to use clinically the following four parameters: SDNN, HRV triangular index, SDANN and RMSSD.

2.2 Frequency-Domain Analysis

The frequency domain analysis (spectral analysis) shows the periodic oscillations of the heart rate signals in the context of different frequencies and amplitudes, as well as information for the relative intensity of the fluctuations of the sinus rhythm of the heart[15]. Many researchers have linked frequency domain measurements to various diseases. The low frequency fluctuations in the heart rate (below 1 Hz) are related in general to the sympathetic and parasympathetic nervous systems, while the high frequency fluctuations result only from the action of the parasympathetic system [2]. The lack of these frequencies can estimate the level of vagal efferent activity [6]. The methods for calculating the spectral density (PSD-Power Spectral Density) are combined into two classes: non-parametric and parametric. A typical representative of nonparametric methods is the FFT (Fast Fourier Transform). In this method, the spectrum is calculated using the Welch periodogram [12]. The RR data is divided into overlapping segments, with overlap fixed at 50%. When analysing non-periodic signals, such as RR intervals, a "spectrum blur" error occurs. The blurring is misleading information regarding the spectral amplitudes and frequencies when analysing the frequency domain data. To reduce the effect of blurring, window functions are applied. In this case, the Henning window function was used. The FFT spectrum is calculated for each window segment, and the segment spectrum is then averaged [13].

The advantages of the FFT method are the following:

- Simplicity of the algorithm used (in most cases fast Fourier transform (FFT) is used);
- High speed signal processing.

The Autoregressive Method (AR-AutoRegressive) is representative of parametric methods. The AR method is based on the assumption that each value of the investigated signal depends on the weighted sum of the previous values of the signal plus noise. The AR model of row p is defined by the following equation:

$$X_t = \sum_{i=1}^{p} a_i X_{t-i} + \varepsilon_t \quad (1)$$

Where:

- ε - noise;
- a – AR parameters.

When analysing digital ECG data, the value of the parameter p is in the range (16-20)..

The advantages of the parametric AR method are:

- Smooth spectral components that can be distinguished from pre-selected frequency bands;
- Easy spectrum processing by automatically calculating signal components at low and high frequencies;
- Easy identification of the fundamental frequency of each component.

The spectral components of the signals are calculated differently for short and long recordings. Short records are 2 to 5 minutes long. There are three main spectral components to be considered [1]: Very Low Frequency (VLF), Low Frequency (LF), and High Frequency (HF). These components are usually captured in absolute values of the signal energy (ms2), but can also be measured in normalized values (n.u.) that represent the relative value of each energy component to the total minus the value of the VLF component. Long records are usually 24- or 48-hour Holter records. These include, in addition to the above three components, a ultra-low Frequency (ULF).

The VLF components of the HRV correspond to the sympathetic and parasympathetic nervous systems, while the HF components correspond only to the parasympathetic activity. Therefore, with the LF / HF ratio of the HRV signal, the level of sympathetic activity of the heart can be estimated, with the increase of this ratio the sympathetic activity increases and, conversely [1].

3. Results and discussion

Two groups of subjects were studied: Group 1 had 10 healthy controls and Group 2- 10 unhealthy subjects (patients with arrhythmia). The results are shown as mean value ± standard deviation. The statistical significance of the studied data was determined by t-test. If a p-value <0.05 is considered to be statistically significant between the 2 groups of subjects studied.

3.1 Time-Domain Analysis

The time-domain analysis measures changes in heart rate depending on the time parameter or measures the intervals between successive normal heart cycles. Table 1 shows the results of the calculations made. The statistical parameters studied: SDNN, SDANN, RMSSD and pNN50 have statistical significance ($p < 0.05$). Therefore, the two study groups can be distinguished to provide an opportunity to assist in the diagnosis of cardiovascular disease.

Figure 1 (top two graphs) shows histograms of a healthy subject and an patient with arrhythmia who allow an accurate representation of the RR interval series distribution. The graph for the healthy subject is symmetrical, dome-shaped and solid histogram, while the graph of the patient with arrhythmia is asymmetric.

In Figure 1 (bottom two graphs), using the geometric method, the distribution of RR intervals is plotted, with the histogram conventionally represented as a triangle. The following two geometric parameters are calculated:

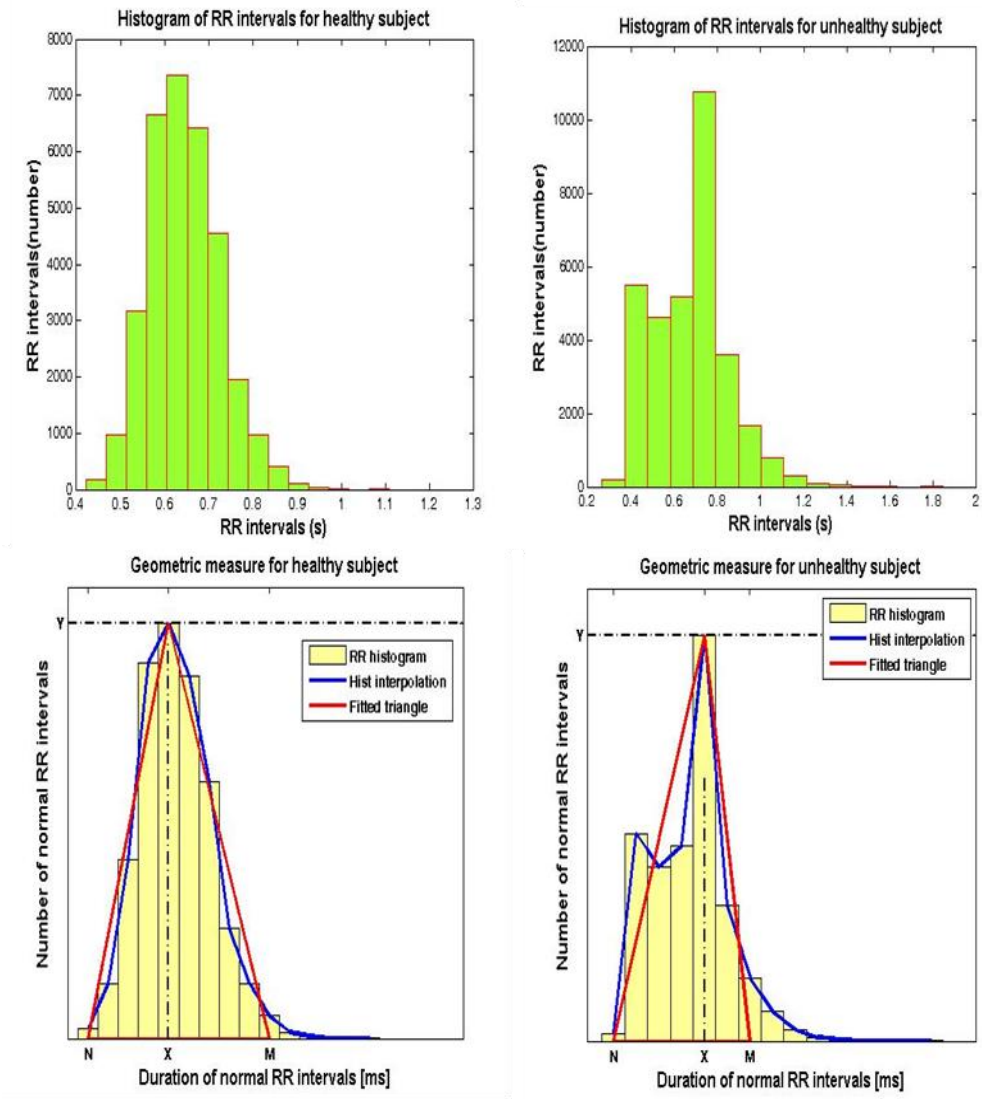
- The TINN parameter is determined by the value of the base of the triangle, measured in milliseconds. The base of the triangle is calculated by the formula: $b = 2A / h$, where h is the largest number of RR intervals and A is the area of the whole histogram, i.e. the total number of all RR intervals analysed. The TINN parameter allows disregarding the RR intervals

Table 1: Time-Domain comparative analysis between healthy and unhealthy subjects

	SDNN[ms]	SDANN[ms]	pNN50	RMSSD[ms]	HRVTi	TINN
Reference value	141±39	127±35	-	27±12	37±15	-
Healthy subject	119±21	98±22	7.1±1.3	30±7	28±11	391±108
Unhealthy subject	160+36	152±41	69±6	103±51	6±2	281±101
p-value	0.006	0.002	0.0001	0.0001	0.0001	0.03

Source: (Authors)

Figure 1: Histograms of RR intervals and Geometric measure for healthy and unhealthy subjects



Source: (Authors)

associated with artefacts and extrasystoles, which form additional peaks and domes of the histogram, as can be seen from the graph shown in Figure1 (bottom right).

- HRVTi is determined by calculating the total number of the RR intervals, which is divided by the peak height of the histogram. The value of this index reflects the total HRV and is directly proportional to the parasympathetic activity.

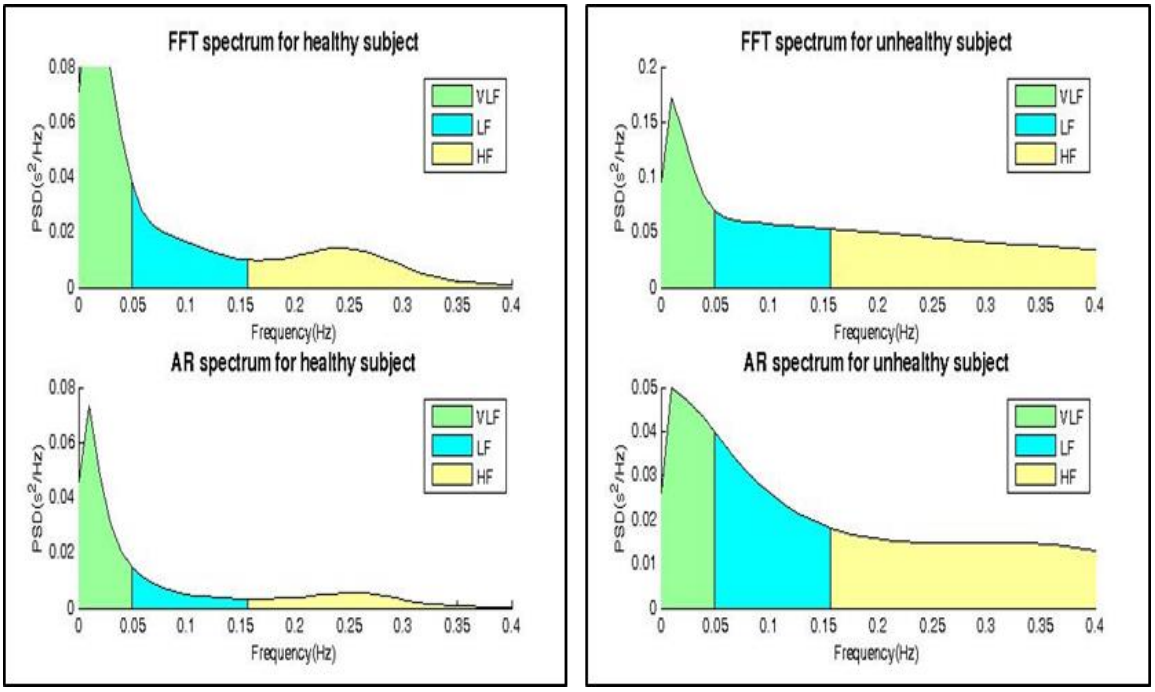
The geometric parameters: TINN and HRVTi have higher values in healthy subjects than patients with arrhythmias, with statistical significance $p < 0.03$. Therefore, the two groups studied can be distinguished by these parameters.

The main advantage of the geometric method is that it is poorly affected by extrasystoles - if for some reason not recognized and removed, it will not lead to any significant changes in the result.

3.2 Frequency-Domain Analysis

Power Spectral Density Analysis (PSD) provides information on power distribution as a function of frequency. In Figure 2 shows the results of the spectral analysis of the two groups studied. Significant correlations are observed between HRV indices obtained by FFT and AR methods in the spectral analysis of patients with arrhythmia on the one hand and healthy controls on the other. Signal energy at low (LF) and high (HF) frequencies measured in ms^2 and normalized units in healthy individuals are within normal range, while in patients with arrhythmia they are outside the range. According to recommendations [1], the LF / HF ratio should be within the range (1.5-2) of healthy individuals. As a result of the spectral analysis performed, this ratio is out of the tolerable range in patients with arrhythmias.

Figure 2: Frequency Analysis for healthy and unhealthy subjects



Source: (Authors)

Table 2: Frequency comparative analysis between healthy and unhealthy subjects

		Total [ms^2] mean±SD	LF[ms^2] mean±SD	HF[ms^2] mean±SD	LF [n.u.] mean±SD	HF [n.u.] mean±SD	LF/HF mean±SD
	Reference value	3466±1018	1170±416	975±203	54±4	29±3	1.5-2.0
Healthy subjects	FFT spectrum	3170±1100	1100±511	908±211	51±4	27±2	1.9
	AR spectrum	2160±1009	520±240	680±105	49±7	28±2	1.7
Unhealthy subjects	FFT spectrum	2090±502	4002±1010	689±121	30±6	59±6	0.6
	AR spectrum	6090±606	1692±501	1535±278	40±2	49±7	0.8
	p-value (FFT)	0.01	0.0001	0.01	0.0001	0.0001	0.0001
	p-value (AR)	0.0001	0.0001	0.0001	0.001	0.0001	0.0001

Source: (Authors)

4. Conclusion

The article presents the results of the analysis of HRV in the time and frequency domain of two groups of people: healthy and cardiac patients (arrhythmia) through the development of a software system for cardio analysis. Through this analysis, objective information about the condition of the sympathetic and parasympathetic systems can be obtained to assist cardiologists in making a diagnosis related to cardiovascular disease. The quantitative dimensions of the parameters studied in this type of analysis have significant clinical application because the boundaries of norm-pathology are known.

Acknowledgment

This paper is an output of the science project "Investigation of the application of new mathematical methods for the analysis of cardiac data" № КР-06-N22/5, date 07.12.2018, funded by the National Science Fund of Bulgaria (BNSF).

References

[1] Malik. M. (1996). Task Force of the european society of cardiology and the north american society of pacing and electrophysiology, heart rate variability—Standards of measurement, physiological interpretation, and clinical use. *Circulation*, *93*, 1043–1065. doi:10.1161/01.CIR.93.5.1043.

[2] Ernst, G. (2014). *Heart Rate Variability*. London: Springer-Verlag.

[3] Peng, C.-K. Havlin, S., Hausdorff, J.M., Mietus, J.E., Stanley, H.E., Goldberger, A.L. (1996). Fractal mechanisms and heart rate dynamics: Long-range correlationsand their breakdown with disease. *Electrocardiol*. vol. 28, pp. 59–65.

[4] Peng, C.-K., Havlin, S., Stanley, H.E. And Goldberger A.L. (1995). Quantification of Scaling Exponents and Crossover Phenomena in Nonstationary Heartbeat Time Series. *CHAOS* vol. 5(1), pp. 82-87.

[5] Rivera, A., Estañol, B., Sentíes-Madrid, H., Fossion, R., C. Toledo-Roy, J., Mendoza-Temis, J., Morales, I., Landa, E., Robles-Cabrera, A., Moreno, R. and Frank, A. (2016). Heart Rate and Systolic Blood Pressure Variability in the Time Domain in Patients with Recent and Long-Standing Diabetes Mellitus. *PLoS One*. Vol. 11(2): e0148378. pmid:26849653. https://doi.org/10.1371/journal.pone.0165904.

[6] Acharya, U.R., Suri, J.S., Spaan, J.A.E., Krishnan, S.M. (2007). *Advances in Cardiac Signal Processing*. Springer-Verlag Berlin Heidelberg.

[7] Kantelhardt, J.W., Zschiegner, S.A., Koscielny-Bunde, E., Havlin, S., Bunde, A., Stanley, H.E. (2002). Multifractal detrended fluctuation analysis of nonstationary time series. *Physica A: Statistical Mechanics and its Applications*, 316(1-4), 87-114.

[8] Kamath, M.V., Watanabe, M.A., Upton, A.R.M. (Ed.). (2016). *Heart Rate Variability (HRV) Signal Analysis: Clinical Applications*, CRC Press Taylor&Francis Group.

[9] Kalisky, T., Ashkenazy, Y. and Havlin, S. (2007). Volatility of fractal and multifractal time series. *Israel Journal of Earth Sciences*, 65, 47-56.

[10] Mulligan, R. 2004. Fractal analysis of highly volatile markets: an application to technology equities. *The Quarterly Review of Economics and Finance*, 44(1), 155-179.

[11] Laborde, S., Mosley, E.; Thayer, J.F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research—recommendations for experiment planning, data analysis, and data reporting. Front. Psychol, 8, 213.

[12] Welch, P. (1996). The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Trans. Audio Electroacoust, 15, 70–73.

[13] Li, K., Rüdiger. H. and Ziemssen. T. (2019). Spectral Analysis of Heart Rate Variability: Time Window Matters. *Front. Neurol.* 10:545. doi: 10.3389/fneur.2019.00545

[14] Escorihuela, R.M., Capdevila, L., Castro, J.R., Zaragozà, M.C., Maurel, S., Alegre, J., Castro-Marrero,J. (2020). Reduced heart rate variability predicts fatigue severity in individuals with chronic fatigue syndrome/myalgic encephalomyelitis. *J Transl Med* 18, 4 . https://doi.org/10.1186/s12967-019-02184-z

[15] Oka, T., Tanahashi, T., Sudo, N., Lkhagvasuren, B., Yamada, Y. (2018). Changes in fatigue, autonomic functions, and blood biomarkers due to sitting isometric yoga in patients with chronic fatigue syndrome. *Biopsychosoc Med.* 12:3. https://doi.org/10.1186/s13030-018-0123-2.

[16] Xhyheri, B., Manfrini, O., Mazzolini, M., Pizzi, C., Bugiardini, R. (2012). Heart rate variability today. *Prog Cardiovasc Dis*. 55:321–31. https://doi.org/10.1016/j.pcad.2012.09.001.