Comparative Heart Rate Variability Analysis of ECG, Holter and PPG Signals

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***Abstract*—The article presents a demonstrative software system with included procedures for input, preprocessing and mathematically based analysis of cardiac data. The created program has the ability to work with the following signals: ECG, holter recordings, PPG signals. The presented system uses real cardiological data from patients and obtained with modern medical devices - electrocardiography, continuous holter monitoring, photoplethysmography device and others. The presented system allows mathematically based study of cardiac records through the use of linear, nonlinear, fractal and wavelet based methods. A comparative analysis was made of the results obtained in the evaluation of the HRV parameters in the three types of signals used. The difference between HRV time series (cardiac intervals and HRV analysis) obtained by examination of individuals diagnosed with heart failure and healthy individuals is graphically presented. The findings indicate that studies of heart rate variability on ECG, Holter and PPG records can be used to support the cardiac practice of physicians.**

***Keywords*—Heart rate variability; cardiovascular diseases; mathematical analysis; holter records; software system**

I. Introduction

The research conducted in recent years has unequivocally shown that heart rate variability (HRV) reflects an individual's health status. HRV [1] presents the variation in time between successive heartbeats (time intervals between heart beats), which variation depends on internal and external conditions. Internal conditions include the work of the physiological systems of the human body, their effective interaction and the general health of man as a result. External conditions include the impact of external circumstances (temperature, weather, emotions, stress, etc.) on the body. HRV is the ability of the human body and in particular of the heart to adapt to constantly changing external circumstances through compensatory reactions.

Usually high values of HRV parameters are an indicator of good health and excellent regulation of the autonomic nervous system. Low values of HRV parameters are an indicator of deteriorating health and disorders in the regulation of the body. The study of many quantitative characteristics of HRV makes it possible to assess how the variability in the parameters of the cardiac series [2] reflects the response of the human body to internal and external factors affecting its physiological and mental health.

HRV can be used to assess the regulation of the autonomic balance of the human body, the work of the heart system and the condition of blood vessels, blood pressure, the work of the digestive system, the nervous system and others.

Heart rate variability can be measured by various mathematically based methods: linear and nonlinear methods, methods based on fractal and wavelet theory, Detrended fluctuation analysis (DFA), Poincare method, methods for estimating the Hurst parameter and many others.

The article uses 3 types of cardiac signals: holter recors, write down from monitoring device for continuous observation; photoplethysmographic (PPG) and electrocardiographic (ECG) recorded with PPG device, capable of simultaneous recording of ECG and PPG signals. When recording the input data, the holter device works in parallel with the PPG device.

In ECG and Holter recordings, heart rate variability parameters are evaluated on RR intervals (determined by the input values of ECG and Holter recordings, R is the maximum point in QRS), and in PPG signal evaluations are performed on PP intervals (P peaks - maximum amplitude deviations of input signal).

The purpose of this article is to present the results of the project "Investigation of the application of new mathematical methods for the analysis of cardiac data", funded by the Research Fund, obtained with a demonstration software system for research and mathematical analysis of cardiac signals and data (obtained by Holter device, and developed demonstration device for write down of ECG and PPG signals). The paper presents the results obtained in time analysis, frequency analysis, DFA and calculation of the Hurst parameter of heart rate variability on three investigated types of real cardiac signals: ECG, Holter records and PPG.

The aim of the article is to present research on the cardiovascular system, made by means of a PPG device developed by the authors and a software system for processing and analysis of cardio data. The software system is designed to work with 3 types of cardio data: PPG, ECG and Holter records, performing preprocessing in accordance with the specific type of cardio data.

The article raises and seeks a solution to the following questions:

- Are the use of the three types of examined cardio (ECG, PPG and Holter records) equally effective in the assessment of HRV and in the analysis of the parameters of HRV data of healthy and sick individuals.
- The problem with the difference of HF parameters in patients with heart failure from those of the studied control healthy group was studied.

- Can PPG, ECG and Holter records be used to differentiate between healthy and sick individuals (and in particular patients diagnosed with heart failure)?

The rest of this document is organized as follows:

Section II provides an overview of related research in the scientific literature on heart rate variability. Section III focuses on the Methodology, HRV data analysis procedures used in this paper (performing mathematical analysis in time domain, frequency domain; fractal analysis and wavelet analysis). Section IV presents the results of the performed experimental analyzes in numerical and graphical form. Finally, Section V presents the conclusions drawn from the results obtained and Section VI presents the direction of future work and perspectives.

II. Review of HRV Studies

Healthy individuals are characterized by good heart rate variability, which results from the body's internal forces to adapt to environmental challenges (physical and psychological). The functioning of the cardiovascular system of a healthy human body can be described by complex mathematical models based on variability in the action of the heart.

HRV is a method for determining the work of the heart, which has been the subject of extensive scientific research over the last two decades on both healthy and diseased individuals. Despite numerous publications on this subject, the method for mathematically based analysis of heart rate variability has not yet been well studied. New methods for the study of HRV are emerging, which need extensive research before being adopted in the daily practice of cardiologists and to be standardized. Particularly valuable in this regard are the findings made on the studied real cardiac records of patients with various heart diseases.

The authors of [3] emphasize the importance of the age and sex of the subjects and the duration of the records made for the results of the HRV analysis.

The research, conducted by Murthy et al. [4] by spectral analysis on PPG records of 5 patients (with atrial fibrillation and myocardial infarction) and 5 healthy individuals showed that PPG signals can be used in the analysis of heart disease. PPG signals were recorded from the earlobes from the earlobes of the subjects.

In publication [5] the authors record and analyze ECG and PPG signals, the recording of which (within 5 minutes) is done simultaneously in time. HRV estimates were performed in the time and frequency domains, and nonlinear mathematical analyzes were performed. However, the recording of the signals is made in ideal conditions (without movement of the studied individuals).

The study done in [6] proposes to improve the efficiency of localization of the maximum deviations in the photoplethysmographic signal through a probabilistic approach based on Bayesian training.

The authors of [7] propose an algorithm based on continuous wave transform (CWT) to detect the maximum deviations of the PPG signal. The algorithm also uses a combination of functions obtained from the applied wavelet transform and indicators evaluating the self-similarity of PPG signals to detect damaged areas of the studied signal.

Studies in [8] compare PPG and ECG signals in terms of determining the HRV time series and accuracy when working with both types of signals. The authors propose a modified algorithm for detecting PP peaks in PPG signals. The obtained results show low statistical errors in determining the HRV time series for both types of studied signals.

Fractal methods for HRV analysis are used by the authors of [9], studying patients with congestive heart failure (CHF) and healthy subjects. The data used are taken from a public database (Physiobank).

The effect of artifacts in cardiac signals (obtained with PPG sensors) caused by movement on HRV and its evaluation using the statistical parameters SDNN and RMSSD was studied in [10]. The authors examined cardiac data obtained from devices worn on the wrist by 22 young and healthy individuals.

A study on 50 healthy young volunteers was presented in [11]. The HRV study was performed on simultaneously recorded photoplethysmographic and electrocardiographic signals using a mobile device. The presented HRV results were obtained using popular public Kubios software.

III. HRV Data Analysing Procedures

The procedures used in the paper for pre-processing and mathematical analysis of the input cardiac data are presented in Fig. 1. The preprocessing includes:

- ✓ Reduction of signal interference, noise and so on;
- ✓ Determination of maximum deviations (R peaks (QRS complexes) in ECG and Holter signals, and P peaks in PPG signals);
- ✓ HRV time series obtained;
- ✓ Determination of normal to normal (NN) intervals from RR intervals time series or PP intervals time series.

The detection of the main points in the cardiac signals - the points with maximum amplitude deviations (R peaks in ECG signals and P peaks in PPG signals) [12] is the starting point in the HRV analysis.

Normal NN intervals are obtained by excluding abnormal strokes such as ectopic strokes from RR/PP intervals (outside the right atrium's sinoatrial node).

Each of the three types of signals studied in the paper (Holter records, ECG, and PPG signals) has its advantages and disadvantages compared to other ways of recording the activity of the heart. Therefore, each case of treatment and prevention of a patient should be considered separately and to determine which method of HRV testing is most appropriate.

ECG signals are obtained in a non-invasive, popular, and widespread way. Electrocardiograms (in cases when they are recorded in an inpatient setting in a polyclinic or hospital) require the placement of several electrodes on the human body in specific places and each of them must be firmly fixed. This is uncomfortable with frequent use of this method (for example, for daily measurements or if several measurements per day are required).

Long-term monitoring of the heart (if you need 24 hours of records and longer for a continuous monitoring of heart activity in risk groups of individuals) is appropriate to perform with a Holter device [13].

Photoplethysmographic signals are an alternative to ECG signals, they are easier to record, PPG devices [14, 15], through which these signals are recorded, are light and comfortable for longer carrying. PPG sensors are small and can be easily integrated into various lightweight and easily portable devices, smart phones and smart watches. In the last few years, with the improvement of the technology for production and miniaturization of PPG sensors, PPG technology enters the daily life of more and more people and becomes an integral part of it. Photoplethysmography determines the time between heartbeats by continuous monitoring of changes in blood volume in part of the peripheral microvasculature [16]. This non-invasive method for measuring pulse waves can also be the basis for HRV analysis.

Determining the health status of an individual is an issue that more and more people are interested in today. Advances in technology have led to an increasing miniaturization of digital sensors, which has led to an increase in the possibility of more accurate and easy continuous monitoring of individuals (eg blood pressure monitoring [17], a parameter that is crucial for the development of a number of diseases) if necessary with the help of mobile devices.

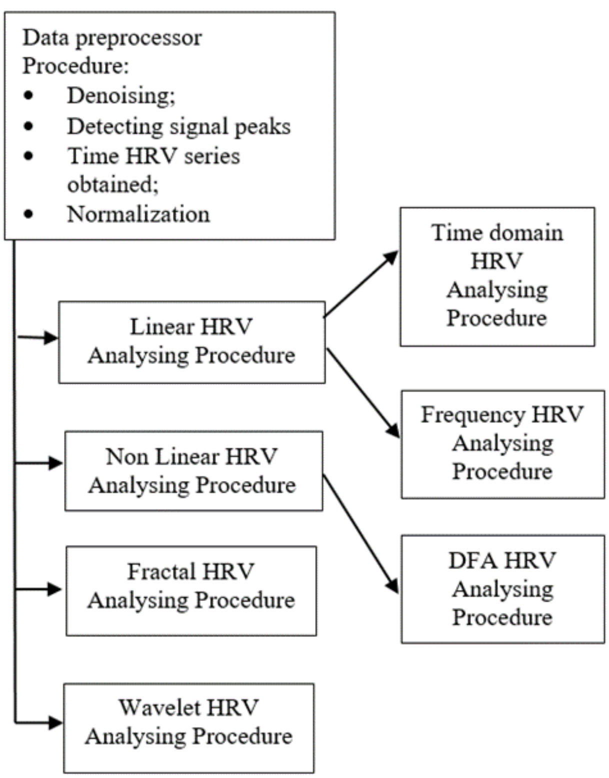

Fig. 1. HRV Analysing Prosedures.

One of the disadvantages of PPG signals is their influence by artifacts [18], which are obtained during the movement of the studied individual. This may adversely affect the HRV score if inaccuracies are found in the localization of the peaks in the PPG signal. In addition, the physiological processes carried out with the help of the heart and the influence of human skin (which may have different characteristics in individual individuals) make it difficult to study HRV in PPG signals.

In this paper, studies of the three types of signals (ECG, Holter, PPG) for recording heart activity were made in terms of assessing heart rate variability.

The article examines HF on short-term cardiac records (2 to 24 hours). Short-term HRV is affected by the cardiovascular system, central nervous system, respiratory system, baroreceptors (blood pressure sensors) and others. Nonlinear estimates of HRV quantify the unpredictability of cardiac time series.

A. HRV Time Domain Analysing Procedure

The parameters in the time domain give numerical expression of the quantitative characteristics of HF for time periods from 2 to 24 hours [19]. The following statistical parameters in time domain were examined in the present study [20]:

- Mean RR (Mean PP) - the mean value of RR and PP intervals;
- SDNN - standard deviation (sd) of normal RR (PP) intervals;
- SDANN - standard deviation of the average normal RR (PP) intervals for each 5 min segment of a 24 h record;
- RMSSD - square root of the mean squared differences between successive RR (PP) intervals;
- SDindex - mean of the standard deviation of all normal RR (PP) for each 5 min segment of the whole record.

The calculations of the presented parameters are performed using the HRV time domain analyzing procedure of the demonstration software system.

B. HRV Frequency Domain Analysing Procedure

The parameters in the frequency domain provide a quantitative assessment of the complexity of the model and the low ability to predict the values of the cardiac series.

The signal energy (Power) in the respective frequency band is determined by the HRV frequency domain procedure. Measurements in the frequency domain show the distribution of absolute power (in ms^2) and relative power (in normal units (nu)) in the studied three frequency bands (Very Low Frequency, Low Frequency and High Frequency).

Frequency domain parameters are based on spectral analysis for the following three components (for short-term records) presented in Table I.

The sum of the three powers (VLF, LF and HF) for short-term recordings gives the total signal power [21].

TABLE I. HRV PARAMETERS IN FREQUENCY DOMAIN

Power [ms^2]	Frequency range [Hz]	Interaction with the systems of the human body
Very Low Frequency (VLF)	0.003-0.04	Sympathetic nervous system
Low Frequency (LF)	0.04-0.15	Sympathetic and parasympathetic nervous system
High Frequency (HF)	0.15-0.4	Parasympathetic nervous system and respiratory sinus arrhythmia.
LF/HF	-	Gives an assessment of the sympathetic balance

The ratio (LF/HF) between LF and HF band powers, known as the sympathetic balance index, assesses the ratio between the activity of the two parts of the nervous system (sympathetic and parasympathetic).

C. HRV Fractal Analysing Procedure

The fractal properties of the three types of studied cardiological data in this paper are determined by analyzing the fluctuations in the time series through the parameters Alpha1, Alpha2 and Hurst.

Detrended fluctuation analysis examines the correlations between RR (PP) interval series in different time scales. DFA defines two parameters: Alpha1 (α_1) – describes short-term fluctuations, Alpha2 (α_2) - provides information on the long-term fluctuations of the studied signal.

The traditional R/S statistical method, most often used in the scientific literature, is used to determine the Hurst parameter in the studied cardiological data [22, 23].

D. HRV Wavelet Analysing Procedure

In the present study, wavelet-based method are used to determine the Power Spectral Density (PSD) of heart rate variability. A graphical method was chosen for the study of global PSD, which allows for visual comparison of the spectral properties of the analyzed signals.

To account for the differences between the HRV parameters determined on the time series of the studied three types of signals, the root mean square error (MSE) is calculated:

$$MSE = \sqrt{\sum_{i=1}^{N}(x_i - y_i)^2}, \quad (1)$$

Where: x – time series of one signal;

y - time series of the second signal;

N- the number of intervals.

IV. RESULTS

Twenty-four individuals diagnosed with Heart Failure were studied (10 men and 14 women aged 52.8 ± 1.6). Records were also made of 12 healthy volunteers without cardiac disease.

The following recordings were made: ECG, Holter and PPG signals of the subjects. Holter recordings are made with a holter monitoring device purchased for the purposes of the research project. ECG and PPG signals are recorded with a multisensor device created according to the scientific project. The created demonstration software determines the RR intervals in the ECG signals and the PP intervals in PPG signals.

In Fig. 2 shows the RR intervals obtained from an ECG signal recorded using a multifunctional PPG device of an individual diagnosed with Heart Failure.

In Fig. 3 presents the RR intervals obtained from the Holter record recorded using the Holter Heart Failure Patient Monitoring Device.

Fig. 4 shows the PP intervals obtained from a PPG signal recorded using the portable PPG device of an individual diagnosed with Heart Failure.

Fig. 5 shows the PP intervals obtained from a PPG signal (via a PPG device) of a healthy individual. The comparison of Fig. 4 and Fig. 5 shows greater variability in the determined PP intervals, which is also proved by the calculated values of the HRV parameters using the methods used in the study (presented in Table II).

All made records of the three types of cardiac signals shown in the figures and participating in the present study were two hours.

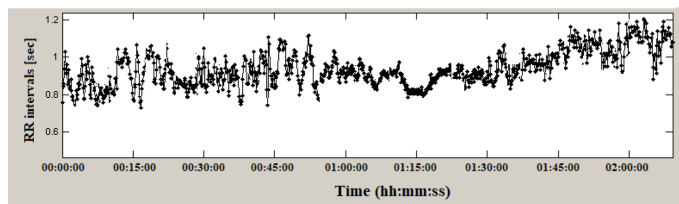

Fig. 2. RR Intervals (ECG Signal, Heart Failure).

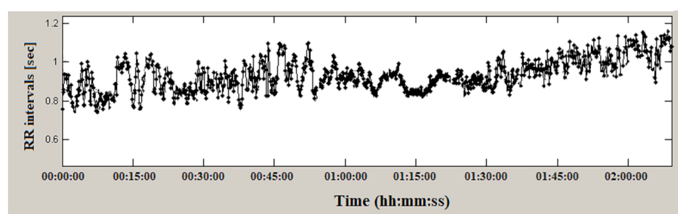

Fig. 3. RR Intervals (Holter Signal, Heart Failure).

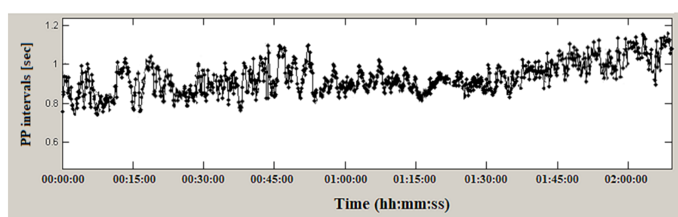

Fig. 4. PP Intervals (PPG Signal, Heart Failure).

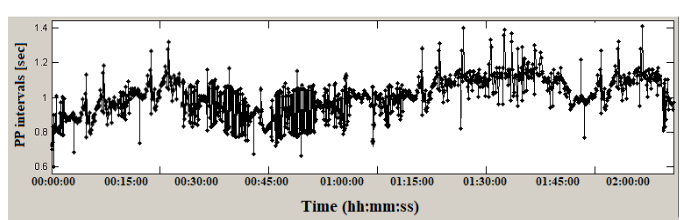

Fig. 5. PP Intervals (PPG Signal, Healthy Individual).

TABLE II. HRV PARAMETERS FOR ECG, HOLTER AND PPG

Parameters		**Group 1 ECG (mean± sd)**	**Group 2 Holter (mean± sd)**	**Group 3 PPG (mean± sd)**
Time Domain Analysis	MeanRR(PP) [ms]	684.22 ±214.68	661.33 ±189.13	692.11 ±223.83
	SDNN [ms]	124.08 ±16.88	118.77 ±24.32	132.66 ±32.09
	SDANN [ms]	98.56 ±34.21	112.01 ±35.43	104.67 ±31.08
	RMSSD [ms]	28.18±8.65	26.35 ±14.15	31.06 ±18.98
	SDindex [ms]	61.33 ± 26.11	64.07 ±22.18	63.88 ±26.44
Frequency Domain Analysis	Power VLF [ms^2]	3098.51 ±654.22	3127.06 ±487.34	2995.78 ±586.39
	Power LF [ms^2]	688.22 ±183.06	691.89 ±243.99	704.05 ±433.01
	Power HF [ms^2]	586.23 ±204.55	582.99 ±244.13	602.33 ±212.03
	Power LF [nu]	0.54±0.19	0.54±0.16	0.53±0.87
	Power HF [nu]	0.46±0.23	0.46±0.43	0.47±0.68
	LF/HF ratio	1.17±0.78	1.19±0.81	1.17±0.93
DFA	Alpha1	1.22±0.24	1.18±0.19	1.23±0.48
	Alpha2	1.28±0.27	1.21±0.22	1.17±0.31
R/S method	Hurst	0.72±0.26	0.74±0.71	0.68±0.14

Table II presents the obtained results of the HRV analysis in Time Domain, Frequency Domain, DFA and hurst parameter (R/S method) obtained from a study of Heart Failure Individuals (n=20).

The results presented in Table II show lower mean values for all three types of cardio signals examined on the frequencies in the Low Frequency band in Power in the indicators of patients diagnosed with Heart Failure compared to the values of healthy patients (691.89 ± 243.99 ms^2 for Holter records versus 1170 ± 416 ms^2 normal values (for healthy people) given in the HRV Standard [20]). The Power HF values for the three types of cardio signals tested were also lower than those recommended in the HRV Standard for Healthy Individuals (582.99 ± 244.13 ms^2 for Holter records versus 975 ± 203 ms^2 normal values given in [20].

The calculated LF/HF ratio, giving information about the balance between Low Frequency band and High Frequency band, has a value of 1.19 ± 0.81 (against 1.5-2.0 recommended value for healthy people [20]).

In the time domain, the following studied parameters show lower values than those recommended for healthy individuals according to [20]: SDNN (max 132.66 ±32.09 ms for PPG against 141±39 ms in [20]); SDANN (max 112.01 ±35.43 ms for Holter records against 127±35 ms in[20]).

Fig. 6 shows the DFA results for Heart Failure Individual. The two studied parameters are alpha1 (shown in cyan color) and alpha2 (shown in red color). The obtained parameters for short correlation values are alpha1=1.26 and for long correlation alpha2=1.28. Fig. 6 shows that alpha1 and alpha2 have similar values in diseased individuals. This shows that in heart disease there is a tendency for short-term and long-term correlations in the HRV series to equalize.

Fig. 7 shows the DFA results for a Healthy Individual. The obtained values for the short correlations are as follows: alpha1 =0.87 and long correlations alpha2=1.24. Fig. 7 shows higher values for the alpha2 parameters relative to alpha1.

Fig. 8 presents a global PSD, drawn using a wavelet-based graphical method of one of the studied Heart Failure Individual (on a record of cardiac data made with a Holter device). The graph shows relatively low values of signal power in all three studied frequency bands (VLF, LF and HF).

Fig. 9 presents a global PSD, drawn by means of a wavelet-based graphic method of one of the examined volunteers without disease (the cardiological record was made with a Holter device). The graph shows high values of signal power in each of the three frequency bands (VLF, LF and HF).

The comparative analysis of the presented global PSDs, shown graphically in Fig. 8 and Fig. 9 shows a decrease in the power of the studied cardiac signal in the studied three frequency bands. This is an indicator of reduced heart rate variability in individuals with Heart Failure.

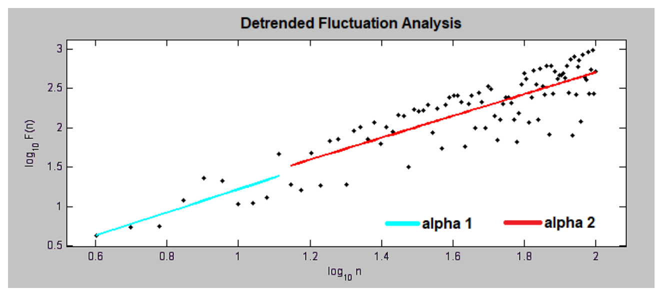

Fig. 6. DFA for Heart Failure Individual.

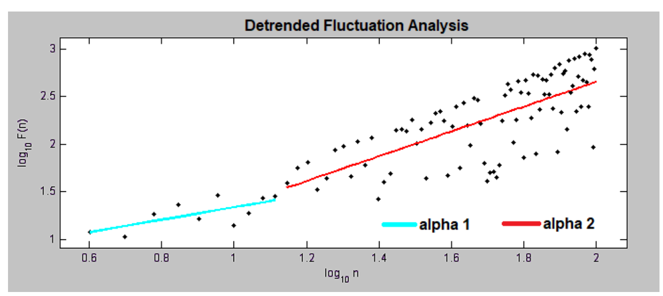

Fig. 7. DFA for an Individual without Disease.

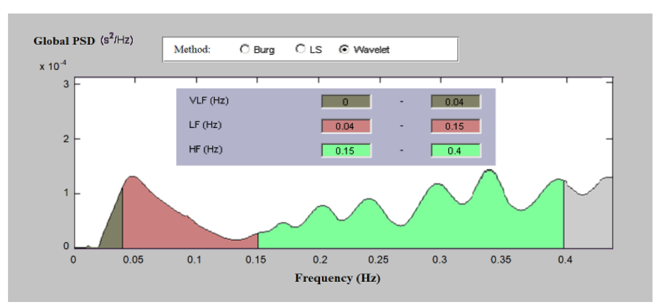

Fig. 8. PSD for Heart Failure Individual.

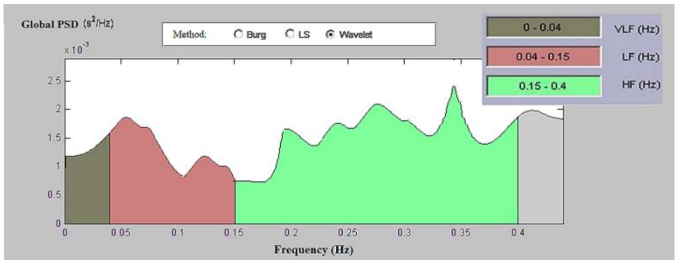

Fig. 9. PSD for an Individual without Disease.

Table III shows the mean squared error calculated by formula (1) for the signals ECG-Holter (MSE_{G1-G2}), ECG-PPG (MSE_{G1-G3}) and Holter-PPG (MSE_{G1-G3}). The smaller the MSE parameter show the closer the two studied time series have values, from which it follows that the two studied methods for determining the cardiac interval give similar results.

TABLE III. RELATIVE ERROR BETWEEN ECG, HOLTER, PPG RECORDS

Parameters		MSE_{G1-G2} **[%]**	MSE_{G1-G3} **[%]**	MSE_{G2-G3} **[%]**
Time Domain Analysis	MeanRR(PP) [ms]	1.34	3.31	0.6
	SDNN [ms]	0.64	1.47	0.88
	SDANN [ms]	1.49	0.69	0.83
	RMSSD [ms]	2.27	3.13	5.27
	SDindex [ms]	4.01	3.18	3.58
Frequency Domain Analysis	Power VLF [ms^2]	2.96	4.92	5.93
	Power LF [ms^2]	3.04	4.07	1.69
	Power HF [ms^2]	4.33	6.71	2.78
	Power LF [nu]	0.04	1.65	1.97
	Power HF [nu]	0.1	1.37	2.06
	LF/HF ratio	0.49	0.08	1.02
DFA	Alpha1	2.44	1.36	3.9
	Alpha2	0.88	1.11	0.82
R/S method	Hurst	0.67	1.03	0.94

From the comparative analysis of the studied data pairs it follows that the relative errors for all examined parameters are less than 4.33% for the ECG-Holter pair, less than 6.71% for the ECG-PPG pair and less than 5.93% for the Holter-PPG pair. The calculated relative errors are small and we can assume that the results obtained in the study of heart rate variability through the three types of signals studied are similar and reliable.

The presented numerical and graphical results are obtained through a demonstrative software system created in the MATLAB software environment.

V. DISCUSSION AND CONCLUSION

The article aims to consider the possibility of interchangeable use of three types of cardio signals in the study of heart rate variability. To solve this problem, MSE errors were determined between the evaluation parameters of each of the three studied types of cardio signals. The results (Table III) show low values of the calculated MSE errors (maximum value 6.71 for MSE_{G1-G3} in determining of Power HF), which is an indicator of the ability to use for correct research each of the three types of cardio signals (ECG, PPG, Holter records). This conclusion is of practical importance, as it proves the possibility of using PPG signals, which have recently become more and more common in human everyday life, for correct analyzes for health purposes.

The other purpose of the article is to examine the possibility of distinguishing healthy individuals from sick cardiovascular patients (more specifically, patients diagnosed with heart failure). The results presented in Table II show that the indicators Power LF, Power HF and LF/HF differ significantly from the corresponding indicators given in the HRV Standard, which is an indicator of the ability to differentiate between healthy controls and patients with heart failure.

The graphical representation of the alpha1 and alpha2 indicators obtained from the application of DFA visually show that these two parameters have similar values in diseased individuals (Fig. 6). The graphical representation of these parameters in Individual without disease (Fig. 7) shows higher values for the alpha2 parameters relative to alpha1. This finding was confirmed for all 24 individuals in the study diagnosed with Heart Failure.

The graphical representation of Global PSD shows low values of global PSD for Heart Failure Individuals (Fig. 8) compared to the values of this parameter in Individuals without disease (Fig. 9). Studies have therefore shown the possibility of graphically distinguishing patients from healthy individuals.

The article presents software procedures for determining heart rate variability, based on mathematical methods for studying three types of signals: ECG, Holter records, PPG. The presented software procedures perform a study of the parameters of heart rate variability in the time domain, frequency domain, apply DFA and determine the hurst parameter of the studied time series.

The parallel analysis of the studied three types of signals shows similar results in the study of heart rate variability and therefore the three methods for HRV analysis can be used equally. The choice of the specific method can be made according to each specific individual case.

The obtained numerical and graphical results show reduced variability of heart rate in the studied individuals with Heart Failure (for example for Holter records Power LF is 691.89 ±243.99 ms^2, Power HF is 582.99 ±244.13 ms^2) compared to healthy individuals. The coefficient showing the state of balance between LF and HF (1.19 ± 0.81) also has lower values in patients with arrhythmia compared to this coefficient in healthy people (1.5-2.0).

The studies in this paper were made on real cardiac records (three types of data were taken: ECG, Holter and PPG) of patients diagnosed with heart failure by a cardiologist as well as on several healthy volunteers.

The use of PPG signals to assess HRV and continuous monitoring of cardiac activity in patients with heart disease in need of long-term monitoring has the following advantages: easy, patient-friendly measurement; efficient signal processing and HRV, use of measuring devices that have increasingly popular and affordable hardware and software solutions; low price and convenience in their use.

VI. Future Work

Procedures for mathematical analysis of the three types of studied HRV signals are to be created with other nonlinear methods, as well as with wavelet-based methods for determining and detailed study of numerical parameters. The results of this study indicate the possibility of a study of HRV parameters in patients with other heart diseases (myocardial infarction, ischemic heart disease, syncope) and creation of an information database for patients.

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References

[1] U.R., Acharya, Suri, J.S., Spaan, J.A.E., Krishnan, S.M. “Advances in Cardiac Signal Processing”. Springer: Berlin. 2007.

[2] G. Ernst. “Heart Rate Variability”. Springer-Verlag London, 2014.

[3] F. Shaffer and J. P. Ginsberg. „An Overview of Heart Rate Variability Metrics and Norms“. Frontiers in Public Health. 2017. Vol.5:258 (pp.1-17). https://doi.org/10.3389/fpubh.2017.00258. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5624990/.

[4] V.S. Murthy, S. Ramamoorthy, N. Srinivasan, S. Rajagopal, M.M. Rao. “Analysis of photoplethysmographic signals of cardiovascular patients”. Conference Proceedings of the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society. pp. 2204-2207, 2001. https://ieeexplore.ieee.org/document/1017209, DOI: 10.1109/IEMBS.2001.1017209.

[5] G. Lu, F. Yang, J. A. Taylor, J. F. Stein. “A comparison of photoplethysmography and ECG recording to analyse heart rate variability in healthy subjects”. Journal of Medical Engineering & Technology. Vol. 33, No. 8, 2009, pp. 634-641, https://www.tandfonline.com/doi/abs/10.3109/03091900903150998?journalCode=ijmt20 https://doi.org/10.3109/03091900903150998.

[6] A. Alqaraawi, A. Alwosheel, A. Alasaade. “Heart rate variability estimation in photoplethysmography signals using Bayesian learning approach”. Healthcare Tech. Letters. Vol. 3, No. 2, pp.136-42, 2016. DOI: 10.1049/htl.2016.0006. https://pubmed.ncbi.nlm.nih.gov/27382483/.

[7] A. Neshitov, K. Tyapochkin, E. Smorodnikova, P. Pravdin. “Wavelet Analysis and Self-Similarity of Photoplethysmography Signals for HRV Estimation and Quality Assessment”. Sensors (Basel). 2021 Vol. 13, No.21(20):6798. DOI: 10.3390/s21206798.

[8] D. Janković, R. Stojanović. “Flexible system for HRV analysis using PPG signal”. In: Badnjevic A. (eds) CMBEBIH, 2017, pp. 705-712. IFMBE Proceedings, vol 62. Springer, Singapore. https://doi.org/10.1007/978-981-10-4166-2_106.

[9] S. Kuntamalla, R. G. R. Lekkala “Reduced Data Dualscale Entropy Analysis of HRV Signals for Improved Congestive Heart Failure Detection”. Measurement Science Review, Vol. 14, No. 5, pp. 294-301, 2014. https://www.sciendo.com/article/10.2478/msr-2014-0040.

[10] A. Rossi, D. Pedreschi, D. A. Clifton and D. Morelli. “Error Estimation of Ultra-Short Heart Rate Variability Parameters: Effect of Missing Data Caused by Motion Artifacts”. Sensors 2020, 20(24), 7122; https://doi.org/10.3390/s20247122.

[11] Ch. K. K., M. Manaswinib, K.N.Maruthyc, A.V.S. Kumard, K. M. Kumar. “Association of Heart rate variability measured by RR interval from ECG and pulse to pulse interval from Photoplethysmography”. Clinical Epidemiology and Global Health. Vol. 10, 2021, 100698. https://www.sciencedirect.com/science/article/pii/S2213398421000026.

[12] B.S. Chandra, C. S. Sastry, S. Jana. “Robust heartbeat detection from multimodal data via CNN-based generalizable information fusion”. IEEE Trans. Biomed. Eng. Vol. 66, No. 3, pp.710-7, 2019.

[13] T. Todorov, G. Bogdanova, N. Noev, N. Sabev. „Data management in a Holter Monitoring System“ TEM Journal, Vol. 8, No.3, pp. 801-805. 2019.

[14] D. J. Plews, B. Scott, M. Altini, M. Wood, A. E. Kilding, P. B. Laursen. “Comparison of heart-rate-variability recording with smartphone photoplethysmography, Polar H7 chest strap, and electrocardiography”. International Journal of Sports Physiology and Performance, Vol. 12, No. 10, pp.1324-28, 2017. DOI: 10.1123/ijspp.2016-0668. https://pubmed.ncbi.nlm.nih.gov/28290720/.

[15] S. Botman, D. Borchevkin, V. Petrov, E. Bogdanov, M. Patrushev, N. Shusharina. „Photoplethysmography-Based Device Designing for Cardiovascular System Diagnostics. International Journal of Biomedical and Biological Engineering“. vol. 9(9), pp. 689-693. 2015.

[16] Clint R. Bellenger, Dean Miller, Shona L. Halson, Greg Roach and Charli Sargent.”Wrist-Based Photoplethysmography Assessment of Heart Rate and Heart Rate Variability: Validation of WHOOP”. Sensors. 2021, 21, 3571. https://doi.org/10.3390/s21103571.

[17] M. Elgendi, R. Fletcher, Y. Liang, N. Howard, N. Lovell, D. Abbott, K., Lim, and R. Ward. „The use of photoplethysmography for assessing hypertension“. Npj Digital Medicine 2:60; 2019. https://doi.org/10.1038/s41746-019-0136-7.

[18] Th.Wittenberg, R. Koch, N. Pfeiffer, N. Lang, M. Struck, O. Amft, and Eskofier, B. "Evaluation of HRV estimation algorithms from PPG data using neural networks" Current Directions in Biomedical Engineering, Vol. 6, No. 3, 2020, pp. 505-509. https://doi.org/10.1515/cdbme-2020-3130.

[19] S. Siecinski, P. S. Kostka and E. J. Tkacz. “Heart Rate Variability Analysis on Electrocardiograms, Seismocardiograms and Gyrocardiograms on Healthy Volunteers”. Sensors. 20, 4522. 2020, DOI:10.3390/s20164522.

[20] M. Malik. “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. 1996. Vol.93, pp.1043–1065. Available: https://www.escardio.org/static_file/Escardio/Guidelines/Scientific-Statements/guidelines-Heart-Rate-Variability-FT-1996.pdf.

[21] F. Shaffer, R. McCraty, C.L. Zerr. “A healthy heart is not a metronome: an integrative review of the heart’s anatomy and heart rate variability”. Front Psychol. 2014, Vol. 5:1040 (pp. 1-19), https://doi.org/10.3389/fpsyg.2014.01040.

[22] U.R. Acharya, K.P. Joseph, N. Kannathal, C.M. Lim, J.S. Suri, “Heart rate variability: a review”, Med. Bio. Eng. Comput, Vol. 44, pp.1031-1051, 2006.

[23] B. Malia, S. Zuljb, R. Magjarevic, D. Miklavcic, T. Jarma, “Matlab-based tool for ECG and HRV analysis”, Biomedical Signal Processing and Control, 2014, Vol. 10, pp. 108-116. http://dx.doi.org/10.1016/j.bspc.2014.01.011.