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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

COMPARATIVE ANALYSIS OF ARRHYTHMIA DETECTION AND PREDICTION METHODS BASED ON MEASUREMENT RESULTS

Speciality: **3337.01– Information, measurement and control systems**

Field of science: **Technical Sciences**

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Baku – 2024

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GENERAL CHARACTERISTICS OF THE WORK

The topicality of the subject. In modern medical practice, the results of reception, registration, processing and analysis of biomedical signals are widely used in the diagnosis of various diseases, in the objective assessment of health, working capacity and physiological state of people, as well as in the development and improvement of diagnostic tools and systems.

According to the statistics of the World Health Organisation, diseases of the cardiovascular system (CVD) have the highest mortality rate and currently remain one of the main causes of death. Among CVD diseases, various rhythm disorders - arrhythmias - occupy a special place. Among arrhythmias, the most common are extrasystoles, which occur outside the basic heart rhythm and manifest themselves as excitation of the heart as a whole or its individual parts. Since ventricular extrasystoles have different gradations in the degree of danger, comparative analysis of algorithms providing their timely detection and classification, development of quality improvement methods is one of the urgent tasks of CVD diagnostics.

The research is based on the works done by Pan J., Tompkins V.J., Rangayyan R.M., Jenkins J.M., Clifford G.D. Laguna P., McFarlane P.V., Sanders W.J., Axelrod S., Ardashev V.N., Gulyaev Y.B, Nemirko A.P., Baevsky R.M. and other scientists who made great contributions to the development of diagnostic methods of CVD.

The object and subject of the research. The cardiovascular system and arrhythmias are the object of research of the thesis work. The subject of the research are methods and systems for detection, recognition and analysis of arrhythmias.

Aims and objectives of the research. The aim of the thesis work is to improve the accuracy of the diagnosis of ventricular extrasystoles through the use of an instrumental method, algorithm, model and programmes for the study of informative parameters of arrhythmias and the results of the study using a priori information. The main objectives of the thesis work are the following:

- Comparative analysis of methods for measuring and processing electrocardiographic signals and analysing arrhythmias;
- Development of software for determining informative parameters of cardiac rhythm;
- Investigation of cardiac rhythm disorders on the basis of echodopplerography method;
- Application of information and probabilistic methods in the diagnosis of arrhythmias;
- Probabilistic evaluation of the diagnosis of ventricular arrhythmias using Bayesian network.

Research methods. Methods of digital bioelectrical signal processing, signal filtering, methods of mathematical statistics and probability theory, Bayesian predictive approach method, methods of computer modelling, MATLAB, Multisim, LabVIEW and Netyca programs were used in the thesis work.

Main issues for review:

- The comparative analysis of methods of measurement, processing and technical means of electrocardiographic signals was carried out, informative parameters necessary for diagnostics of arrhythmias of heart rhythm, according to the results of ECG-signals analysis, were determined. [1, 6, 11, 15, 19,21].

- On the basis of modern virtual technologies the research of heart rhythm model was carried out, ECG signals were modelled in LabVIEW medium, element base was modelled in Multisim14 medium and electrocardiograph model was built by joint synthesis of these two media. [8, 10, 16].

- A new method of arrhythmia recognition based on the analysis of the sequence of RR-interval ratios was proposed, its algorithm was built and programmed, and its adequacy was determined by testing with test signals. [6, 18, 20].

- A comparative analysis of the results of joint application of ECG and echodopplerography technologies was carried out and it was found that there is a correlation between the deviation (increase) of the thickness of the arterial vessel wall rejection complex and cardiac arrhythmia; analysis of the Doppler blood signal in the frequency-time domain, an algorithm for determining informative parameters and computer modelling was implemented and a modified geometric method was proposed to improve the accuracy of calculating the maximum frequency of the Doppler blood signal. [2, 7].

- A Bayesian network for the diagnosis of extrasystoles was developed using Netica software and used to predict and estimate the probability of ventricular arrhythmias. [3, 4, 17. 20].

Theoretical and practical significance of the research. In order to reliably identify arrhythmias, an algorithm was developed for the sequence of steps required to perform ECG signal processing and QRS complex detection procedures in accordance with the requirements of the AAMI EC57:2012 documents. The system developed in this research to study heart rate variability and arrhythmias, as well as the Bayesian confidence network built for prediction and probabilistic assessment of ventricular arrhythmias in clinical practice, can allow physicians to reliably identify arrhythmias and improve the accuracy of medical decisions.

Approbation and application. The results of the research of arrhythmias in the thesis, the developed method, algorithm and programmes were used in the state research works and in the educational process of students of the department of “Instrumentation Engineering” of Azerbaijan State Oil and Industry University, Baku. It was used in the diagnosis of ventricular extrasystoles in “Omur” clinic.

The main scientific and practical results were discussed at seminars of the Department of Instrumentation Engineering of Azerbaijan State Oil and Industry University and at subsequent international conferences.

21 scientific works, including 10 articles, 11 scientific-conference materials, 4 articles without co-authors, corresponding to the topic of the dissertation work, were published. Of these, 1 are

indexed in "SCOPUS" and 1 in "Web of Science" scientific databases.

The dissertation is realized at: Dissertation work Ministry of Science and Education of the Republic of Azerbaijan, Azerbaijan State Oil and Industry University, Department of "Instrumentation Engineering" and the "Omur" clinic in Baku.

Personal involvement of the author: The purpose of the dissertation work, the propositions defended, comparative analyses, the developed new algorithms, the performed mathematical calculations, the obtained simulation and experimental results belong to the author personally.

Scope and structure of the dissertation: The dissertation was written in accordance with the requirements set by the Supreme Attestation Commission under the President of the Republic of Azerbaijan. The dissertation consists of an introduction, four chapters, a conclusion, two appendices and cited literature.

The introduction of the dissertation is 16701, chapter I 59976, chapter II 73986, chapter III 34025, chapter IV 67073 characters, the result is 2906 characters, and the text is interpreted in a total of 254667 characters.

BRIEF CONTENT OF THE CASE

The introduction substantiates the relevance of the thesis subject, explains the objectives and problems of the research. The results containing scientific innovations are noted and their practical value is indicated.

In **Chapter 1** of the thesis, in order to analyse the state of the problem and formulate the research problem, the physiological basis of heart rhythm, methods of analysis of rhythm variations, advantages and disadvantages of modern instrumental methods used in the research of arrhythmias are considered.

The peculiarity of arrhythmias is that they can occur asymptomatically and at random times, so that arrhythmias are often not detected during ECG recording. Because arrhythmia episodes occur irregularly, prolonged (sometimes more than 24 hours) patient monitoring is necessary, which is currently performed with Holter monitoring. Automated ECG processing is necessary to analyse the large amount of information obtained from monitoring and to assist specialist physicians in making treatment decisions. In the process of automatic ECG analysis, there are a number of difficulties associated with the physiological origin of electrocardiographic signals. These include non-determinism, variability, non-stationarity of electrocardiographic signals, sensitivity to interference from numerous obstacles and noise. These characteristics of electrocardiographic signals, in addition to the need to develop noise-resistant algorithms for their automatic processing, analysis and detection of arrhythmias in real time, also impose certain requirements on modern computer technology. But as the level of development of modern computer technologies has sufficient technical capabilities to implement these procedures, the main issue is a comparative analysis of existing algorithms for the detection of arrhythmias in accordance with the recommendations of AAMI 57-2012[1] and processing of ECG signals for their detection (arrhythmias) in a more qualitative form and stages of analysis. For this purpose, as already mentioned, first of all it is necessary to compare existing methods of ECG processing and analysis among themselves.

The methods of statistical and time (Time Domain Methods), frequency (Frequency Domain Methods) and non-linear analysis of heart rate variability (HRV) are considered and the main parameters characterising HRV obtained as a result of their analysis are determined. When using these methods, the cardiorhythm (CRG) - a series of consecutive RR intervals - is considered as a function of time.

The main diagnostic methods used in the diagnosis of arrhythmias (Electrocardiography (ECG), Holter monitoring, Echocardiography (IV-CG) and additional diagnostic methods (Transesophageal echocardiography, Physical exercise test) are explained and their different features in arrhythmias are highlighted.

The chapter concludes by explaining the mathematical methods used in diagnosis and justifies the application of the mathematical method used in diagnosis based on the Bayesian criterion, the Bayesian confidence network, in assessing the probability of diagnosis of arrhythmias.

In **Chapter 2** describes algorithms for removing noise and obstacles in ECG signals, filtering methods in the time and frequency domains, and modern algorithms for detecting arrhythmias from ECG and Holter ECG results. On the basis of comparative analysis of these algorithms, a sequence of stages of ECG processing and analysis is proposed to improve the accuracy of arrhythmia classification. Computer models of heart rate variability and algorithms of arrhythmia detection, developed software and methods of testing their efficiency are described.

The general scheme of the ECG recording process is presented in Fig. 1. The primary signal is amplified by an optically isolated instrumental amplifier, and then the amplified signal passes through an high-pass filter (HP) to a second amplifier and then to a smoothing low-pass filter (LP). Finally, the amplified and filtered signal is passed to an analogue-to-digital converter (ADC) and the output of the ADC generates the ECG signal.

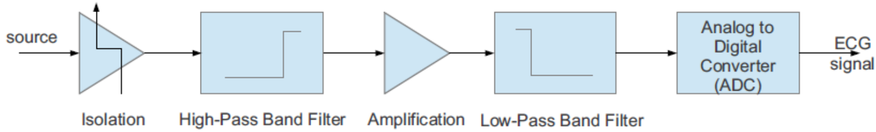

Figure 1. General scheme of ECG recording

Various distortions of ECG elements arise as a result of the influence of a number of interferences and obstacles when taking ECG signals. Most electrocardiographic obstacles can be divided into several groups according to their manifestations on the recorded ECG (and according to the methods of their elimination). The following disturbances have the greatest impact on almost all ECG measurements:

- the impact of electrode polarisation causing a zero level shift in the signal;
- quasi-harmonic process represented by the components of the industrial frequency caused by the mains voltage;
- artefacts, represented by spikes of random amplitude and duration that may occur as a result of electrode displacement;
- electrophysiological, mainly myographic obstacles.

The impact of these noises and obstructions on the ECG signal is additive. By properly arranging the recording system, obstacles caused by electrode polarisation and grid voltage can be compensated for and their effects minimised. Myographic obstacles are a major obstacle. Myographic obstacle is a non-stationary process. In the patient’s resting state, the standard square of variation of myographic obstacle is a few microvolts and increases dramatically with increasing physical activity. Certain errors can be expected in the results of automatic diagnostics when different types of obstacles interfere with the ECG.

Algorithms and filtering methods of interference suppression in ECG signals. One of the main requirements for ECG signal processing algorithms is the maximum preservation of Q, R, S ridges, and smoothness extrema of P and T peaks, as well as prevention of obstacles interference. In heart rhythm disorders, ECG may show splitting of peaks, small peaks, pathological ridges and specific deformations of QRS complex and ST segment, which are very important to preserve during processing. Therefore, the selection of ECG dynamic filtering algorithm should be based on the set goal. The main problems of eliminating the influence of noise or interference on ECG signals are:

- high level of noise or obstacles, low level of useful signal;
- non-stationarity of the signal and obstacles;
- intersection of signal and obstacle spectra;
- removal of the obstacle without reducing the quality of the investigated signal.

In order to reduce the impact of noise and obstacles on ECG diagnostic systems, two main directions are emphasised.:

- methods of protection against noise and obstacles;
- methods of noise and obstacle reduction.

Table 1 describes the noises and methods of protection against them.

Table 1

Methods of protection of ECG signals from interference

Types of obstacles	Protection methods
1. Movement artefacts	Improvement of electrode designs and means of their fixing. Improvement of contact medium.
2. Network obstacles	Application of instrumental amplifiers with high in-phase attenuation coefficient. Reduction of skin-electrode resistance. Insulated working part, working grounding. Arranging the accuracy of research conducting.
3. Muscular tremor	Reducing the resistance of tissues, especially skin. Arranging the accuracy of research conducting
4. Drift of the isoline	Increasing the input resistance of the amplifier, reducing skin resistance. Improvement of electrode designs and means of their fixation.

Among the preprocessing methods, an important place is occupied by the analysis of different types of artefacts that distort ECG signals and filtering methods used to eliminate them without reducing the quality of the useful signal. Filtering methods are distinguished depending on the area in which they are performed: time or frequency domain.

They use international databases of certified ECG signals to test and compare the performance of different arrhythmia detection methods in real signal processing under the same conditions. These databases are equipped with annotations made by medical experts and the results mentioned here are considered 100% reliable and are considered “reference signals” when comparing different algorithms.

PTB Diagnostic ECG database, MIT-BIH Arrhythmia Database and MIT-BIH Normal Sinus Rhythm Database were used in this work. The front panel and structural diagram of the programme for analysis and determination of informative parameters of CVD in Labview software environment are not shown in Figure 2. The programme is built according to the following algorithm.

- reading of the studied ECG signal (file)
- Distinguishing and measuring the time intervals between RR waves (RR intervals) of the ECG.
- building dynamic sequences of cardiointervals
- determination of CVD parameters on the basis of analysing the obtained series by various mathematical methods.

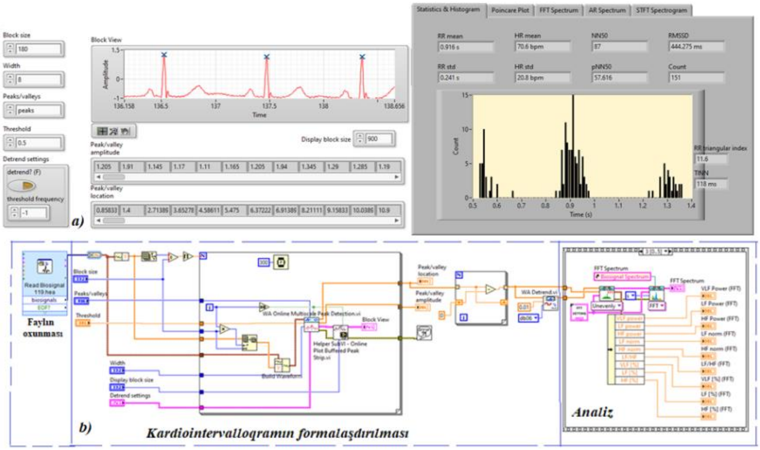

Figure 2. Front panel *(a)* and structural diagram *(b)* of the programme for analysis and informative tuning of CVD parameters in *Labview* software medium

The subroutine of cardiointervalogram formation is shown by dotted lines in Fig. 3, *b*. This is a programme (virtual device) that detects ECG signal peaks based on wavelet analysis to determine the sequence of RR intervals in the online mode. We created this programme based on the *WA Online Multiscale Peak Detection VI* virtual device.

The subroutine of heart rate variability analysis and determination of its informative parameters was developed using the *Sequence Structure* element of Labview package and consists of 6 frames (0...5) or, in other words, 6 subroutines. With the help of these programmes such parameters as NN50, pNN50, RMSSD, HR std, HR men, RR std, RR men, histogram of RR intervals and triangular index TINN, scatterogram, Fast Fourier Transform of cardiointervalogram (FFT-Fast Fourier Transform) and spectral parameters are determined, autoregression spectrum (AR autoregression) and corresponding spectral parameters, short-term Fourier Transform (short-term Fourier Transform) and corresponding spectral parameters.

As an example, Figure 3 shows one of the CVD analysis subroutines, fast Fourier transform, of file 119.*hea* from the MIT BIH[1] database.

Arrhythmia detection and recognition algorithm. Currently, there are many methods for detecting normal and pathological QRS complexes, which are practically formed based on improvements of previously known methods. These improvements include the elimination of various obstacles and noise, based on the application of various transformations for reliable detection and recognition of arrhythmias.

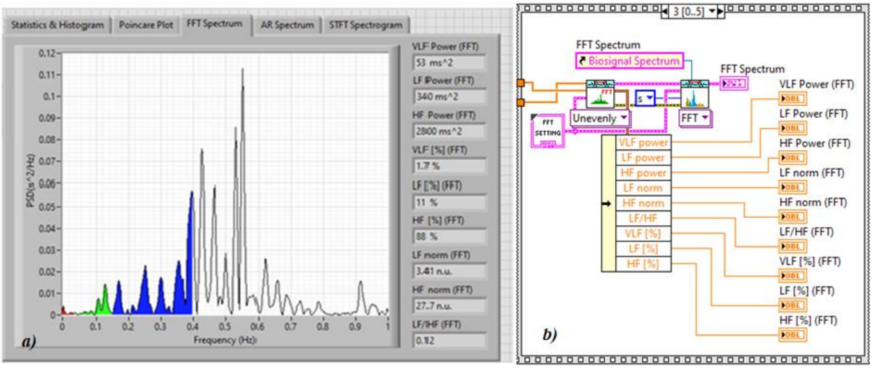

Figure 3. Analysis of file 119.*hea* taken from the MIT BIH database: FFT- Fast Fourier Transform: *a* – front panel, *b* - structural diagram

However, the problem of unpredictability of rhythm dynamics in an isolated patient still remains open and raises the question of improving algorithms for detecting QRS complexes and creating algorithms that are weakly patient-specific. In this regard, we propose a new algorithm based on the analysis of the correlation of these intervals, in contrast to the existing algorithms for arrhythmia recognition, based mainly on the comparative analysis of the differences between the RR intervals and their mean values. It is known that the RR interval variation in arrhythmias is ≥10%. Based on this, we can say that the ratio of two neighbouring intervals ΔR_{i-1} to ΔR_i in a normal rhythm state:

$$\frac{1}{1,1} \leq a_i \leq \frac{1,1}{1},$$

or

$$0,9 \leq a_i \leq 1,1 \qquad (1)$$

must satisfy the condition, where $a_i = {R_i}/{R_{i-1}}$. In the case of a normal rhythm, condition (2) should be fulfilled regardless of the absolute lengths of neighbouring intervals (it depends very little on a particular healthy rhythm). Thus, the essence of our proposed algorithm is as follows.:

1) The ECG data file under study is uploaded to the system (or recorded online),

2) The amplitude and localisation of R-ridges are distinguished,

3) The sequence of RR-interval lengths $\{\Delta Ri= Ri\text{-}Ri\text{-}1\}$ is determined;

4) The new sequence of elements a_i is defined as the ratio of neighbouring RR-intervals according to the obtained series of RR-interval lengths: $\{ai= \Delta Ri/ \Delta Ri\text{-}1\}$.

5) The number of extrasystoles or rhythm disorders is calculated by the number of a_i values that fulfil the conditions $a_i \leq 0,9$ or $a_i \geq 1,1$. These conditions correspond to the appearance of pathological intervals, i.e. correspond to beat frequency changes of at least 10%. If the number of a_k values corresponding to pathological intervals is exactly n_k, the number of arrhythmias (extrasystoles) is determined by the formula $n_e=n_k/3$.

6) Diagnostic parameters (sensitivity, specificity) and temporal localisation of extrasystoles are determined by the number of rhythm disorders.

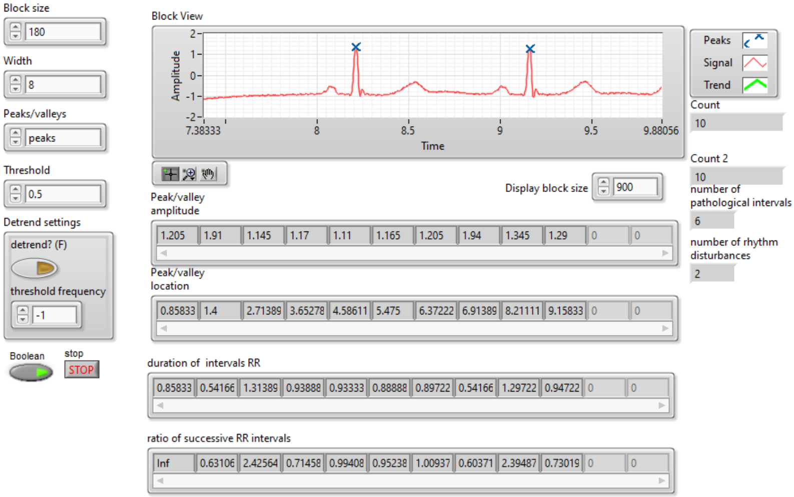

Figure 4. Front panel of the programme for implementing the arrhythmia detection algorithm in LabVIEW medium

This algorithm was implemented in the LabVIEW 2014 software medium. Figure 4 shows the front panel of the programme. The programme consists of three subroutines: file reading, cardiointervalogram (CIG) generation and signal analysis..

System for determining diagnostic parameters of ECG signals in phase space. From a given scalar ECG signal s (t) in time domain: to vector representation in phase coordinates s(t), s'^ (t) (where s (t), and s'^ (t) are instantaneous values of the value and derivative of the ECG signal, respectively switching allows to effectively restore the useful signal distorted by excitations, to divide s (t) into separate R-R intervals, to identify atypical cycles. One of the advantages of phase portraits of ECG signal is that when describing ECG in phase coordinates s (t), s'^ (t) its traditional diagnostic features are revealed more clearly than in the time domain. Figure 5 shows the structural diagram of the programme we use in LabviewW medium to determine the diagnostic parameters of ECG signals in phase space. To make sure that the programme is compiled correctly, a known signal (sine or cosine) is fed to the system input using *Simulate Signal* VC and the plot of its derivative is checked (since the derivative of sine gives cosine). The investigated and stored signal is read with *Read Biosignal* VC, filtered with *Filter* VC and then output with Derivative (dX/dt) VC..

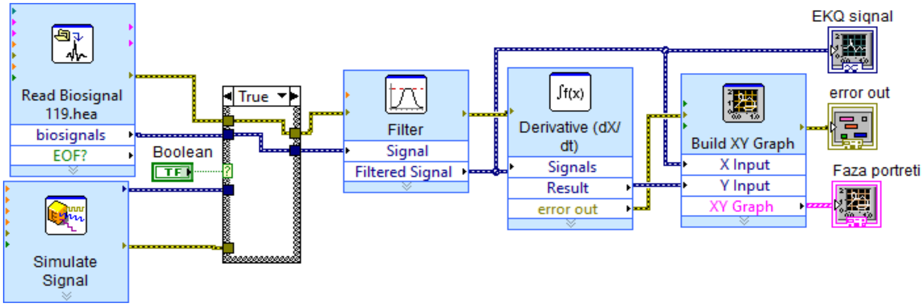

Figure 5. Structural diagram of ECG signal processing programme in LabviewW medium

The phase portrait of the ECG input signal is plotted as the dependence of ds/dt on s(t) in the two-dimensional XY coordinate system. Figure 6 shows ECG images and corresponding phase portraits of data files *e0103.hea and 119.hea* taken from Physionet international database. As can be seen from the figure, the phase portrait of a patient with normal sinus rhythm (file e0103.hea, Figure 6,a) is clearly different from the phase portrait of a patient with arrhythmia (file 119.hea, Figure 6, b).

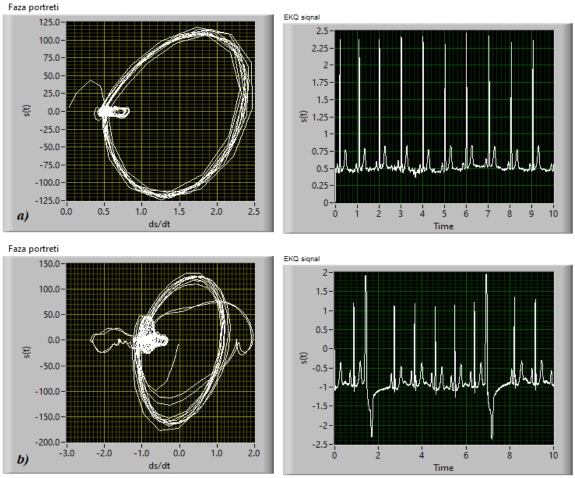

Figure 6. ECG images and their corresponding phase portraits of data files *e0103.hea* and *119.hea* from the Physio-net international database.

Based on a comparative analysis of studies related to heart rhythm, it is suggested that arrhythmias can be distinguished and classified by ECG signals when investigated according to the following scheme:

1. *Selection of a database to analyse the performance of different methods and algorithms for arrhythmia detection and classification*.
2. *Initial processing*.
3. *Segmentation*:
4. *Selection of signs*
5. *Classification*
6. *Evaluation*.

In **chapter 3**, the assessment of CVD condition based on exodopleurography techniques was considered. Atherosclerosis is considered to be the most common and life-threatening disease of CVD. Atherosclerosis develops in parallel with coronary heart disease, and strokes and heart attacks can occur as a result of vessel blockages. A blood vessel consists of a vascular wall and a wall cavity. The vascular wall consists of three layers: the outer layer - adventitia; the middle layer - media, the inner layer - intima. It is the deviation (increase) in the thickness of the intima-media complex of the common carotid artery that is considered to be the first marker of atherosclerosis and coronary heart disease. Ultrasound methods are considered to be the most accurate method of measuring intima-media complex (IMC) thickness.

We performed echocardiographic studies using ambulatory sheets of 142 patients and the results of their cardiological examinations at Omur clinic to determine the correlation between changes in the intima-medial layer of the vascular wall and cardiac rhythm disorders. We first divided them into four groups according to the 0-3-point grading of arrhythmias according to the Laun and Wolf classification of CVD status. We compared the results obtained by measuring the IMC thickness of the aortic and brachial arteries of patients of all four groups with the “arrhythmic” states of the patients. The results of measuring the intima-media complex layer thickness of the aorta and brachial arteries are shown in table 2.

Table 2

Intima-media complex layer thickness of branch vessels and aortic arteries of patients of groups I-IV.

Groups	Age, *year*			Thickness of the IMC bass, *mm*			IMC thickness of the aorta, *mm*		
	medium	min	max	medium	min	max	orta	min	max
I	39,37±1,408	30	53	0,573±0,007	0,46	0,69	2,740±0,088	2,10	3,80
II	39,50±0,542	33	49	0,592±0,007	0,51	0,81	2,790±0,007	2,20	3,70
III	41,60±1,247	33	57	0,644±0,009	0,54	0,76	3,51±0,10	2,45	4,60
IV	39,38±1,409	31	53	0,698±0,015	0,66	0,76	4,06±0,16	3,60	4,80

It was found that the average concentration of the intima-media complex layer of the brachial artery increased by 3,3%, 12,4% and 21,8% in patients included in groups II-IV compared to the control group (group I). The mean concentration of the aortic artery intima-media complex layer in patients included in groups II-IV increased by 1,8%, 28,1%, 48,2%, respectively, compared with the control group.

Our results show that there is a correlation between the deviation of the intima-media complex layer thickness of brachial and aortic arteries, i.e. increase, and gradational extrasystoles.

Various numerical methods are known for determining the zone of maximum frequency from the Doppler spectrum: *percentage method, simple and modified threshold methods, geometric and modified geometric methods.* There are some difficulties in estimating the maximum frequency by these methods (Fig. 7), for example, in estimating the maximum frequency by the geometric method:

1) the maximum distance between the integral spectrum curve $\Phi(f)$ (ISC) and the reference line being sensitive to the amplifier ratio, i.e., f_L and f_B being different, as can be seen in Fig. 7;

2) when the blood flow direction is changed, the flow may not be detected in some spectral columns, in which case it is formed only by the noise power and not by the signal power.

Based on the improved geometric method, it is proposed to overcome the above drawbacks, the estimation of the maximum frequency is carried out as follows:

1) In order to eliminate the sensitivity due to the amplifier ratio, the curve of the normalised integral spectrum should be used, i.e. ISC should be replaced by ISC/ISC_{max}. In this case, the algorithm for finding the maximum frequency will be carried out using the curve (assume that the GED is a normalised ISC, then ISC_{max} is equal to the total energy of the signal in the frequency range under study, equal to the value of $\Phi(f)$ at point D in Fig. 7)

2) In order to eliminate the effect of noise, the empiric ISC of the power should be entered into the threshold limit (the threshold value in Fig. 7 corresponds to the DR) and the straight line CR should be taken as a reference line (Fig. 7, b);

3) The value of the maximum frequency must be equal to the abscissa of point Z, where the distance between the ISC reference line and CR is maximum.

Since blood flow rate varies depending on the phases of the heart rhythm: systole and diastole, and since the velocities of the elementary volume of erythrocytes in the part of the ultrasound beam falling on the blood vessel at a given moment have different values, the Doppler signal of blood flow at any given moment covers a wide band of frequencies. With such a complex and dynamically changing non-stationary signal, it is necessary to use methods to analyse this signal in the frequency-time domain in order to obtain informative blood flow parameters. We performed spectral-temporal analysis of the Doppler signal based on the Gabor transform. Gabor transform is a type of Windowed Fourier transform with a Gaussian window $W(t-\tau) = e^{-\frac{(t-\tau)^2}{\sigma^2}}$ and is defined by the following expression:

$$G(\tau,\omega) = \int_{-\infty}^{\infty} s(t) exp(-\frac{(t-\tau)}{2\sigma^2}) \exp(-j\omega t)\, dt \qquad (2)$$

Where τ and σ determine the shift and width of the Gaussian window, respectively.

We performed the Gabor transformation of the Doppler signal in the LabVIEW software medium (Fig. 8). We obtained the Gabor spectrogram of the signal using the virtual device *Fast Gabor Spectrogram VI* from *Time Frequency* Analysis - frequency-time palette of the programme. *Blood Flow Doppler* model of the initial Doppler signal was generated using the *Data Samples VI* element. We obtained a spectrogram of the Doppler blood flow signal using a virtual system that we developed using the *Fast Gabor Spectrogram VI* function in *LabVIEW*, which performs a fast Gabor transform and the structural diagram of which is shown in Figure 8,A.

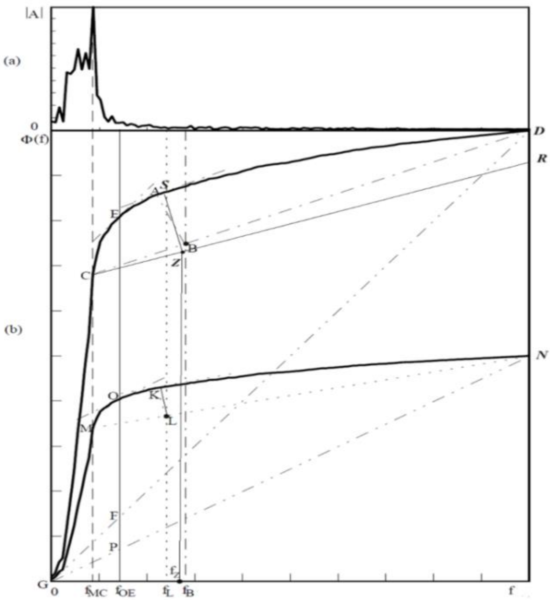

Fig. 7. GED and GON curves (b) plotted as a function of different amplifier ratios of the Doppler spectrum (*a*) and its integral spectrum (*b*)

The velocity *v* of erythrocytes was calculated according to the Doppler shift f_d by the formula $v = \frac{f_d}{2v_0 \, cos\alpha} c$. In order to define f_d, we fed the output signal of the "*Fast Gabor Spectrogram VI"*to the *"Mean Instantaneous Frequency VI"* input, in which the output of the latter indicates the value of the instantaneous average frequency. To calculate the blood flow velocity *v*, we included the frequency f_0 of the US transmitter (f_0= 5 MHs=5000000 Hs), insolation angle α (α=60^0), diffusion velocity *c* of ultrasound in tissue as initial data (*c= 1540 m/sec*). The velocity calculation program is presented on the structural diagram (Fig. 8, A), and the calculation results are shown on the front panel (Fig. 8, B).

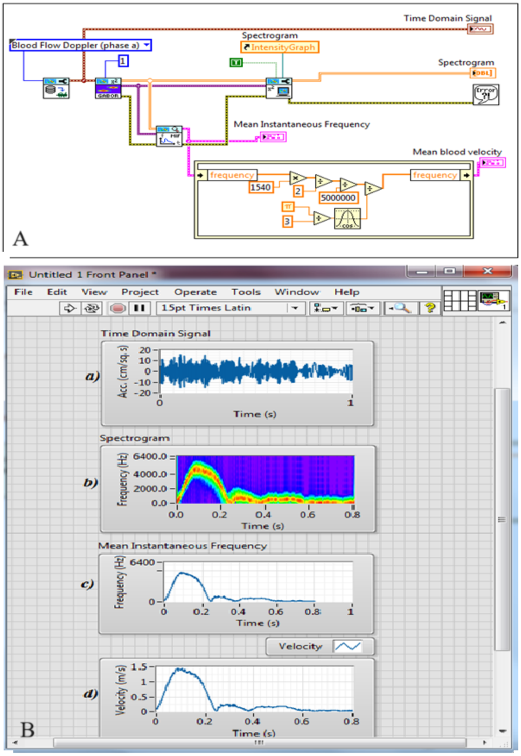

Figure 8. Program of frequency-time analysis of Doppler blood flow signal in LabVIEW software medium

In **Chapter 4**, the application of Bayesian network in the probabilistic assessment of arrhythmia diagnosis is discussed. In the process of diagnosis, the issue of uncertainty in the information provided arises, since usually the same symptoms can be associated with several diseases. Bayesian Belief Network is widely used in medical expert systems to manage such uncertainty. The essence of BBN is the probabilistic assessment of a posteriori information, i.e. diagnosis of the disease, when certain a priori information about the disease and research results is available using Bayes' theorem. BBN is a probabilistic graph model and is graphically described by acyclic directed graphs (directed arrows, which represent links between nodes - conditional probabilities) and graph nodes (i.e. variables, in our case diseases, symptoms) (DAG, directed acyclic graph). Nodes correspond to certain variables associated with the process under study and are defined by a table of conditional probabilities.

Firstly, the following should be carried out for the probabilistic assessment of the arrhythmias diagnosis:

1) the selection of ventricular extrasystole to be investigated should be justified;

2) initial data on ventricular arrhythmias should be collected (examination results and history, i.e. symptoms), instrumental studies (electrographic and Doppler studies) should be performed for diagnostic procedures, and finally,

3) In order to build a BBN, it is necessary to select a software medium, set up the network structure, compile the network and using the created BIS, a probabilistic assessment of the diagnosis of the selected type of ventricular arrhythmia should be performed.

In this research, we considered the grading of ventricular extrasystoles according to the Laun-Wolf classification. According to this classification, the gradations of ventricular extrasystoles are graded by a 5-point system.

Precise identification of gradations in the diagnosis of ventricular extrasystoles is of great importance for the selection of treatment tactics.

Based on the Laun-Wolf classification of ventricular extrasystoles, extrasystoles corresponding to points 4 and 5 of the above gradations and considered very life-threatening are very well visible on a normal ECG and it is not difficult to distinguish them. But the selection of extrasystoles in gradation 0-3 points requires long-term ECG Holter monitoring and solving a difficult problem. Among these gradations, especially the 3-point gradation can at any time move to more dangerous gradations if preventive measures are not taken. In this sense, timely detection and diagnosis of ventricular extrasystoles corresponding to the 3-point gradation according to the Laun-Wolfe classification is of great importance. The study investigated ventricular extrasystoles corresponding to this 3-point gradation.

Since the research process was conducted on the basis of incomplete and unreliable data taken from the outpatient charts of patients admitted to Baku Omur Clinic, we used BBN to diagnose ventricular arrhythmias. Bayesian belief networks are more often used to make judgments under uncertainty, to provide better decision making, including disease diagnosis, choosing the best course of treatment for a patient, predicting the consequences of diseases and modeling diseases. Therefore, this work addressed the development and application of BBN for the diagnosis of ventricular arrhythmias. Outpatient charts of 142 patients examined in “Omur” clinic were used as initial data for BBN information support, Baku city.

The software *Netica*, a product of the Canadian company “Norsys Software Corp” was used to build the BBN.

To build a Bayesian network in the Netica software, a table of diagnostic conditional probabilities is compiled on the basis of the initial data. Such a diagnostic table includes diseases (diagnoses) D_1,D_2, ..., D_m, belonging to a certain class of diseases, symptoms S_1, S_2,..S_n, related to these diseases, and a set of conditional probabilities corresponding to $p(S_i/D_k)$.

If a patient is diagnosed with D_k (i.e., the event D_k has occurred), the probability of observing a particular symptom S_i associated with that disease is called the conditional probability (“S_i if D_k”) and is denoted as $p(S_i/D_k)$. For example, the conditional probability $p(S_2/D_1)$

$$p(S_2 \cap D_1) = p(D_1) \cdot p(S_2/D_1) = p(S_2) \cdot p(D_1/S_2)$$

$$p(S_2/D_1) = \frac{p(S_2) \cdot p(D_1/S_2)}{p(D_1)} \qquad (3)$$

is determined on the basis of Bayesian theorem expressed by formula (3).

If a symptom S_i associated with disease D_k is observed in a patient during a test examination, the probability of correctly diagnosing D_k based on this symptom (this conditional probability is denoted as $p(D_k/S_i)$) is calculated by Bayesian theorem as follows:

$$p(D_k/S_i) = \frac{p(S_i/D_k) \cdot p(D_k)}{p(S_i)} \quad (4)$$

The diagnosis procedure is performed based on not a single symptom, but on several symptoms observed in the patient S_{ci}= (S_1, S_3, S_6, S_7, S_9, S_{10}, S_{11}, S_{14}) and the reliability probability of the diagnosis D_k for this set of symptoms is expressed by Bayesian theorem as follows:

$$p(D_k/S_{ci}) = \frac{p(S_{ci}/D_k) \cdot p(D_k)}{p(S_c)} \quad (5)$$

The conditional probability $p(S_{ci}/D_k)$ of the symptom complex in expression (5) is determined by the probability multiplication formula.

$$p(S_{ci}/D_k) = p(S_1/D_k) \cdot p(S_3/D_k) \cdot p(S_6/D_k) \cdot \ldots p(S_{14}/D_k) \quad (6)$$

To find the conditional probability of the entire symptom complex, the conditional probabilities of the individual clinical symptoms can be multiplied if these probabilities are independent of each other. The $p(S_c)$ in (5) represents the total probability and expresses the probability of having a symptom complex in all diseases and is defined as follows:

$$p(S_c) = \sum_{i=1}^{m} \sum_{k=1}^{j} p(S_{ci}/D_k) \cdot p(D_k) \quad (7)$$

where *i* is the number of symptoms and *j* is the number of diseases (in our case arrhythmias) manifested by these symptoms.

When calculating the diagnosis of several different diseases on the basis of a set of symptoms observed in a patient, S_{ci} takes into account the fact that each symptom has a different probability for individual diseases.

Based on our results and data taken from the literature, a table of conditional probabilities of symptoms for diagnosing D_4 was compiled (Table 4).

Table 4

The table of conditional probabilities of symptoms (diagnosis D_4) of ventricular extrasystoles belonging to group 4.

Symptoms	The probability of having symptoms with the disease
S_1 heart stops and then palpitates	69%
S_2- sudden freezing of the heart between palpitations after eating followed by rhythmic beating for about 1 minute	22%
S_3 - sudden stoppage of the heart, and subsequent palpitations, when assuming a horizontal position, and especially when lying on the left side	9%
S_4- the number of ventricular extrasystoles more than 30 per hour	23%
S_5 - Oxygen saturation index of blood erythrocytes <22	11%
S_6 -Measurement of the intima-media layer thickness of the aortic artery >3,370 mm	41%
S_7 - frequent and polytopic ventricular extrasystoles	19%
S_8 – Age limit >40	15%

We built the Bayesian network in the Netica program in the following order:

1. Insertion of variables (nodes). The constructed network consists of 9 nodes: 8 symptom nodes and 1 diagnosis (disease) node.

2. *Establishing cause-and-effect relationships between nodes*. Once all nodes have been created, placed, and the unconditional probabilities of their properties have been determined, they are connected to each other by the cause-and-effect relationship between them.

3. *Tables of conditional probabilities of dependent nodes*. Conditional probability tables are defined for each of the dependent nodes.

4. Compilation of Bayesian network. After determining all conditional probabilities between the nodes of the network, it is necessary to compile it. As a result of compilation, the operation of calculating the values of conditional probabilities of non-marginal nodes of the network is also performed. Figure 15 shows the description of the Bayesian network in the Netica software for the diagnosis of ventricular extrasystoles.

According to the Laun-Wolf classification, the probability of having a 3-point ventricular extrasystole in a patient with the symptoms listed in table 4 is 59.9%, as can be seen in figure 9, based on the results of the BBN we installed in the Netica medium.

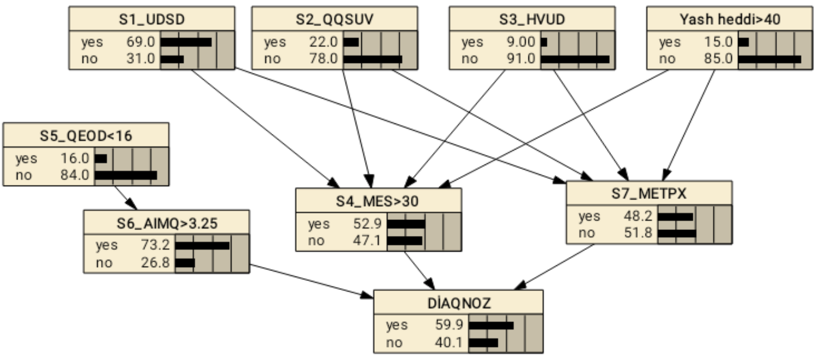

Figure 9. Description of Bayesian network in Netica software. The names of nodes (variables) correspond to table 4.

Known algorithms for the detection of ventricular extrasystoles are based on the method of electrocardiography, that is, registration, processing and detection of QRS complexes and accurate registration of their position on the time axis. A distinctive feature of our work is that in the diagnosis of ventricular extrasystoles in combination with the ECG method, Doppler-echocardiographic studies determine other factors that play a role in the occurrence of arrhythmias, including the index of oxygen saturation of blood erythrocytes, the value of the intima-media layer concentration of the aortic artery, as well as the lipid content in the plasma comprehensively considered the influence of changes in the number of fractions.

The proposed Bayesian network allows tracking the dynamics of changes in the posterior probability by manipulating the conditional probabilities of symptoms.

The quality of probabilistic estimates is improved by adding additional nodes to the network.

The main difficulties encountered in working with Bayesian networks include the lack of a general choice and rule for constructing the network structure, the need to know a large number of conditional probabilities for complex systems, and sensitivity analysis, which is a difficult task as a complex technical problem.

The Bayesian belief network developed for the diagnosis of extrasystoles in the Netica software can provide physicians with additional opportunities for refinement and important decision making.

THE MAIN RESULTS OF THE DISSERTATION WORK

1) A comparative analysis of methods and technical means of ECG-signals measurement and processing was carried out and informative indices necessary for diagnostics of heart rhythm disorders were determined according to the results of ECG-signals analysis [6, 11, 15, 19, 21].
2) On the basis of modern virtual technologies the efficiency of models of heart rhythm research in technological processes is substantiated and their simulation modeling in *LabVIEW* and *Multisim* media is carried out [8, 10, 16].
3) A virtual system for determining and studying diagnostic parameters of ECG signals in phase space was developed and applied in the analysis of arrhythmias [5, 6, 19].
4) The methods of mathematical processing used in the study of heart rate variability were analyzed; the processing of ECG signal by these methods was carried out using *LabVIEW* medium and the possibilities of its *Biomedical Toolkit* extension [6, 8, 10].
5) The program (front panel and structural diagram) of the virtual device for heart rate variability analysis is designed and implemented in *LabVIEW* medium [6, 10].
6) A new algorithm for arrhythmia recognition based on the analysis of RR-interval ratios has been proposed and investigated. The algorithm has high sensitivity and specificity to ECG signals accompanied by sinus rhythm and single ventricular extrasystoles. The advantage of the algorithm is its simplicity and minimal requirements for computational resources [6, 18, 20].
7) A comparative analysis of the results of joint application of ECG and echo-dopplerographic technologies was carried out and it was found that there is a correlation between deviation (increase) of intima-media complex thickness of the arterial vessel wall and heart rhythm disturbances. [12, 13, 17];

8) Analysis of Doppler blood signal in the frequency-time domain, an algorithm for determining informative parameters and computer modeling were implemented and a modified geometric method was proposed to improve the accuracy of calculating the maximum frequency of the Doppler signal from the spectrum [2, 7, 9].
9) Along with the theory of signal processing in the diagnosis of ventricular extrasystoles, the feasibility of using image recognition and medical expert systems - BBN was noted, a table of conditional probabilities of extrasystole symptoms was compiled and the posterior probability of extrasystole was estimated with a Bayesian network using conditional and a priori probabilities [3, 4, 17. 20].
10) To improve the efficiency of arrhythmia detection and diagnosis in combination with the ECG approach, other factors determined by Doppler-echocardiographic study and important in the occurrence of arrhythmias are used, including the index of erythrocyte oxygen saturation in the blood, the value of the intima-media layer thickness of the aortic artery and the amount of lipid fractions in the blood plasma. The influence of such factors as BBN changes is comprehensively taken into account [13, 14, 17].

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Personal activity of the candidate in cases with co-authors:

[1, 2, 8]- Development of the structural scheme of the system of signal processing and analysis, justification of the choice of the main

wavelet, study of the issues of improving the quality of ECG-signals registration.;

[3,4]- Development of diagnostic features derived from the study of ventricular arrhythmias for a Bayesian network;

[6, 10, 18]- Proposal of a new method of automatic detection of ventricular arrhythmias and implementation of its algorithm in Labview software medium;

[13, 17]- Representation of initial arrhythmia data for a Bayesian network, construction of a table of conditional probabilities of ventricular extrasystole symptoms;

[7, 9]- Analysis of the Doppler signal of blood flow in the frequency-time domain and investigation of factors affecting blood flow rate;

[15, 21]- Classification of arrhythmias based on ECG monitoring devices and studies related to correlation of cardiac results with other diagnostic data.

The defense will be held on the November 29th, 2024 at 15:00 at the meeting of the Dissertation Council ED 2.04 of Supreme Attestation Commission operating under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

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Dissertation is accessible at the Azerbaijan Technical University Library.

Electronic version of the abstract is available on the official website of the Azerbaijan Technical University.

Abstract was sent to the required addresses on October 29th 2024.

Signed for print: 23.10.2024
Paper format: A5
Volume: 39095
Number of hard copies: 100