

NOVEL PC-BASED CARDIAC STRESS TEST SYSTEM

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Abstract – Novel PC-based cardiac stress test system is considered in this paper. The system consist of ECG signal acquisition module, which is connected to the PC over USB port, software application dedicated to stress testing, ergotest bicycle and treadmill. First, electronic circuits of signal acquisition module are described, and after, software features are presented.

1. INTRODUCTION

An electrocardiogram (ECG) is the recording of electrical activity generated by the heart on body surface [1]. Pathological changes and events in heart activity are detectable in electrocardiogram in advance before they show some visual harmful effect.

ECG signal, in form of the voltage potentials, is collected by conductive electrodes placed at designated locations on human body. The typical ECG signal with relevant features is given in Fig.1. The signal is characterized by a recurrent wave sequence labeled by successive letters of alphabet (P, Q, R, S, T and U) [1].

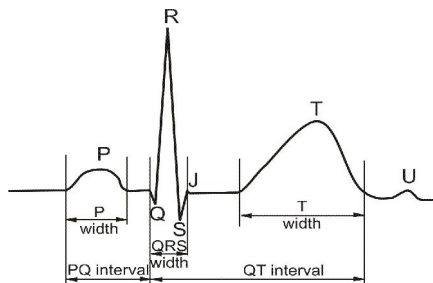


Fig. 1. Typical ECG wave with relevant features

The ECG signal shape and the time intervals (P width, PQ interval, QRS width, QT interval, T width etc. shown in Fig.1) are significant for electrocardiographic diagnosis. Disorders in electrocardiogram predict the fault heart functioning. But, these disorders often occur sporadically and cannot be seen in short term recording. They can appear in situations when patients are under some kind of physical or mental stress. Therefore, it is mandatory to perform ECG signals recording during the stress test. This paper proposes novel electrocardiograph device dedicated to stress testing..

2. ECG SIGNAL ACQUISITION SYSTEM

Proposed ECG signal acquisition system represents 12-channel electrocardiograph for exercise testing. Interfaced to PC, system can record, display, achieve, present and analyze ECG recordings. The system consists of module connected to PC over the USB port and the software application that runs in Windows operating system.

The acquisition module collects the potential signals from patient's skin over conductive electrodes. The standard 12 ECG leads (D1, D2, D3, aVR, aVL, aVF, V1, V2, V3, V4, V5 and V6) require 10 electrodes placed at designated points

on the human body. Four of them (named R, L, F and N) are placed on arms and legs and other six on chest.

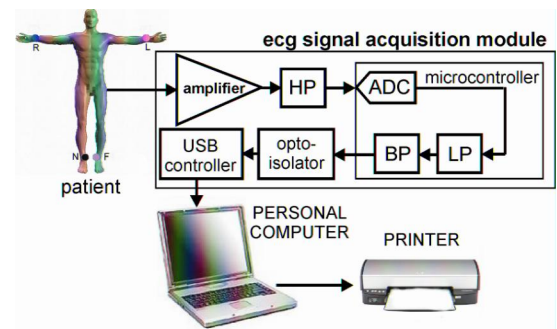


Fig. 2. Block diagram of ECG acquisition system

The simplified block diagram of the ECG recording module is shown in Fig.2. The signals received from the electrodes are buffered and connected to the inputs of resistor network inside the module. Resistor network gives at outputs 12 ECG lead signals - D1, D2, D3, aVR, aVL, aVF, V1, V2, V3, V4, V5 and V6. Beside, the resistor network gives at one of its outputs the common-mode signal (the R, L, and F average signal) which is amplified by inverting amplifier and then connected to the neutral electrode N. This applies an inverted version of common-mode interference to the patient's right leg, with the aim of cancelling the interference.

The module amplifies and filters the ECG leads signals. After analog-to-digital conversion, the microcontroller, the part of the module, further processes the data in digital domain and then sends the data to the USB controller. The software application receives the data sent over USB and displays the ECG signals on the PC monitor.

In the paper, first, the overview of the ECG amplifier circuit concept is presented. Then, the digital circuits are proposed, which perform the analog-to-digital conversion, digital filtering and data streaming to PC over USB. After, the software features are described.

2.1 ECG amplifier circuit concept

The ECG signal amplifiers embedded in the module take signals from sensors and amplify them to the amplitudes required for AD conversion. The analog part of a system must deal with extremely weak signals ranging from several μV up to 5mV. The useful bandwidth of ECG signals is from 0.05Hz – 100Hz [1].

The ECG signal, collected from patient's skin over conductive electrodes, is combined with significant DC component which is several hundred times greater than the amplitude of ECG signals [2]. The DC component is caused by the contact between the electrode and patients skin and has to be eliminated by high-pass filters [2].

Beside DC component, ECG signals can be corrupted by various kind of noise [1].

- power-line interference: 50Hz pickup and harmonics from power mains that are several dozen times greater than useful signal.
- patient's respiration, motion artifacts and electrode contact noise cause variable resistance between the electrode and skin that generates the fault baseline drift of ECG signals.
- muscle contraction adds fault signals that are mixed with the ECG signals.
- electromagnetic interference from other electronic devices also adds noise to ECG signals.

The main performance characteristics of ECG analog amplifiers can be summarized as follows:

- frequency band at 3dB from 0.05Hz to 100Hz with the first-order high pass filter [2]
- tolerance of DC input voltages (the level depending on type of the electrode)
- overall gain in range 200-1000 (46dB-60dB) with the maximal input signal of $\pm 5\text{mV}$ without output stage saturation [1],[3]
- differential input impedance should be greater than $10\text{M}\Omega$ in the entire frequency band [2].
- common mode rejection ratio CMMR is greater than 80dB

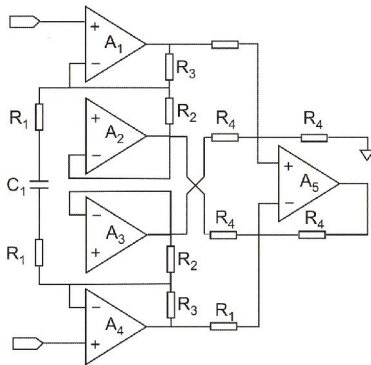


Fig.3. The ECG amplifier circuit concept

The ECG amplifier circuitry is made of operational amplifiers and passive components (resistors and capacitors). Operational amplifiers are low power and have 3.3V voltage supply. The block diagram of the ECG amplifier circuit [3] is shown in Fig. 3. The differential input signal is buffered and then filtered by first order high-pass filter consisting of resistor R1 and capacitor C1 [3]. The values of R1 and C1 are chosen to give cut-off frequency of high pass filter equal to the value of 0.05Hz. The A1 and A2 amplifiers take one half of the differential input AC signal and form the first amplifier [3]. The A3 and A4 amplifiers take the other half of the differential input signal and form the second amplifier. The gain of amplifiers is given by following equation:

$$A_d = 1 + \frac{R_3}{R_1 \parallel R_2} \quad (1)$$

The last stage of amplifier circuit (consisting of A5 operational amplifier and resistors R4) is unity gain subtraction circuit [3]. The proposed ECG amplifier amplifies both the ECG signal and 50Hz signal which is several times greater than ECG signal. To avoid amplifier's output saturation, signal gain of the amplifier circuit (A_d) is chosen to be only 150.

Power-line interference is eliminated after AD conversion is performed, and digital filtering, implemented in

microcontroller's program. The A3, A4 and A5 operational amplifiers are selected to have low offset voltages and A1 and A2 with high gain-bandwidth product. The measured common mode rejection of analog signal processing chain ratio is nearly 100 dB.

2.2 Digital signal processing and power supply of ECG signal acquisition module

The ECG acquisition module, beside ECG signal amplifier circuits, consists of microcontroller, optocouplers, communication block and power supply circuits. The module is connected to personal computer over USB serial port which 5V power supply lines are used as the module's power supply.

Analog signals are sampled with the sampling frequency of 500Hz which is more than enough for ECG and pulse signal monitoring purpose. The AD converter, incorporated in microcontroller, provides 12-bit data resolution on its output. After AD conversion, digital samples are digitally filtered by microcontroller's software. Two digital filters are implemented: the low-pass and band stop filters. The low pass digital filter has cut-off frequency of 100Hz and band-stop filter eliminates the 50Hz power-line interference signal.

After the data has been processed by microcontroller, they are sent to the optocoupler ICs which are used for digital signal isolation. The patient safety standards demand that the isolation voltage between the devices power supply and patient should be at least 4000V [2]. Digital isolation is necessary for data transmission to PC. Therefore, optocoupler circuits with high transmission rates and high isolation voltage are chosen as digital isolators. The maximal isolation voltage of 5000V of chosen ICs satisfies the strict standards. After digital isolation, data is fed to the input of to an USB to RS232 converter IC, and sent to PC.

The power supply of the module is brought from PC over USB port. Not only the digital signals, but also the power supply had to be isolated. Therefore, DC-DC converter IC, with the isolation voltage of 5200V, is used for power supply isolation. It receives 5V supply from USB and provides isolated 3.3V. The 3.3V voltage is used to supply microcontroller and operational amplifiers within the analog signal processing block. The total power dissipation of the circuits inside the module is 0.35W. The circuits consume current of approximately 70mA at 5V power supply voltage.

The one of the major requirements of novel ECG signal acquisition module is that the module should be lightweight and easily portable. The module enclosure's dimensions are only 105x58x18.5mm and weight is only 200g. This demanded that only surface-mount components had to be used on the printed circuit boards within the module.

3. SOFTWARE APPLICATION FOR STRESS TESTING

The software application is comprehensive high-end application dedicated to stress cardiac testing. It runs in Windows operating system and has user-friendly graphical interface.

The application has been developed in Microsoft Visual C++.NET 2005 [4]. It provides plenty of useful features for recording and analyzing the ECG signals. The application is designed to be simple and intuitive, and, because of this,

ECG acquisition module can be used immediately with minimal operator training. Main benefits of the application are:



Fig.4. User interface during the stress testing

- records 12-channel electrocardiogram during exercise test and displays it on PC monitor in real-time
- software controls the whole exercise test process and sends commands over RS232 PC interface to digitally controlled bicycles and treadmills. Several commercial bicycles and treadmills are supported.
- ECG recordings and analysis results are printed on printer that is connected to the PC
- data management system gives the ability to store unlimited number of recordings with full analysis
- the recordings and stress test results can be sent over the internet in form of JPEG picture or PDF file

The user interface of program for stress testing is shown in figure 4. ECG signals are displayed on the left side in the main window of the application. The amplitude of ECG waves in the main window can be determined by comparing with the grid made of horizontal and vertical lines. The distance between two consecutive grid lines corresponds to actual size of 5mm.

The ECG signals can be divided into one or two columns. When displayed in one column, the user of program can choose one of the possible values for time-base sensitivity 25mm/s or 50mm/s corresponding 10s or 5s time interval presented on the screen. In the other option, time-base sensitivity values 25mm/s and 50mm/s correspond to time intervals 5s and 2.5s. The time-base value of 25mm/s is most frequently used; the other two values are useful for detailed signal analysis.

The amplitude sensitivity of ECG signals can be set to one of three values 5mm/mV, 10mm/mV and 20mm/mV. The selected sensitivity can be applied to the all signals on the screen or to the only particular one specified by the user. Beside setting the sensitivities of time-base and size, the user can turn on and off particular leads and therefore setup the screen in his/her own manner.

During the exercise test the patient is riding the ergo-meter bicycle or is walking on the treadmill, while the doctor is watching and analyzing the patient's ECG signals. Usually, the test doesn't last longer than 30 minutes. The test consists of several phases or stages. At the test beginning, the patient

is in resting state. As the test proceeds, the load of ergo-meter bikes and speed and angle of treadmill are gradually increased. The standard test protocols define the load values for each stage and the time moments when load changes. The software supports standard stress testing protocols Bruce, Balke, Naughton, Ellestadt, Cooper, etc. Beside, the doctor can define his/her own protocols. At the end of the test, patient is again in the resting phase when the doctor analyzes the ability of patient heart to rest.

In the main window, above the ECG signals, the application provides three graphs (Fig.4) containing the valuable measurement results helping the doctors in making the correct diagnose of patient's health status:

- graphs of heart rate [5] and load with relation to time
- trend graphs of amplitude and slope of ST segment [6]- ST level and ST slope (the part of the ECG signal relevant for detecting the ischemic heart disease) for ECG leads D2 or V5
- graphs showing the instantaneous values of ST segment level and slope for all selected leads

Numerical values for heart rate (HR), maximal allowed heart rate (Max HR), blood pressure (BP) and time elapsed from the test beginning are showed on the right side, next to the graphs.

The control part of the window on the right side provides control buttons for:

- searching the database for the record
- storing the currently made record into database
- stress test process control (starting, stopping, changing the load levels during the test, getting into Recovery stage)
- storing the current event into the exercise record (set of ECG signals currently shown in the main window).

During the test, up to 15 ECG recordings can be stored automatically (after the stage-defined time has elapsed) or manually (by the doctor). After the test has finished, recordings can be opened and analyzed.

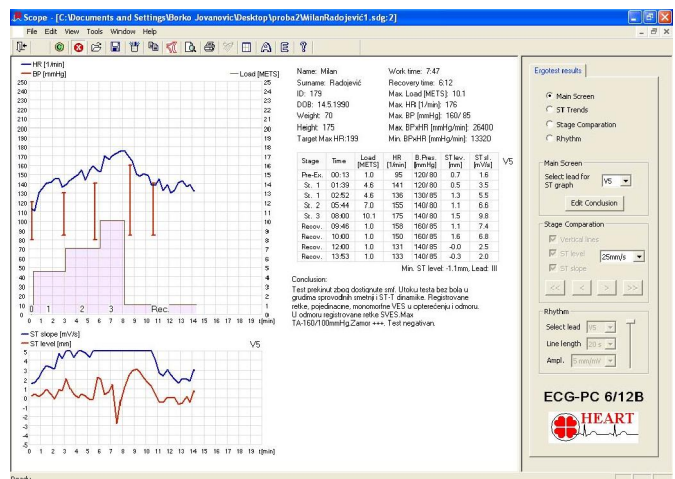


Fig.5 Exercise test results: Main results window

During the exercise test, currently acquired signals (of 12 standard ECG leads D1-D3, aVR, aVL, aVF, V1-V6) are compared with the referent ones that are stored at the beginning of test.

After the test is completed, the program presents the results in the four windows:

- Main results
- Stage comparison
- ST trends window
- Complete ECG window

The Main results window (Fig.5) gives the following:

- Patient related information: name, surname, date of birth, height, weight, target heart rate frequency
- Relevant stress test results: work time, recovery time, maximally achieved load, heart rate and blood pressure values frequency during the test.
- Table with relevant information for specific stages during the test: time, load, heart rate frequency, values of blood pressure, ST level and slope.
- Doctor's conclusion

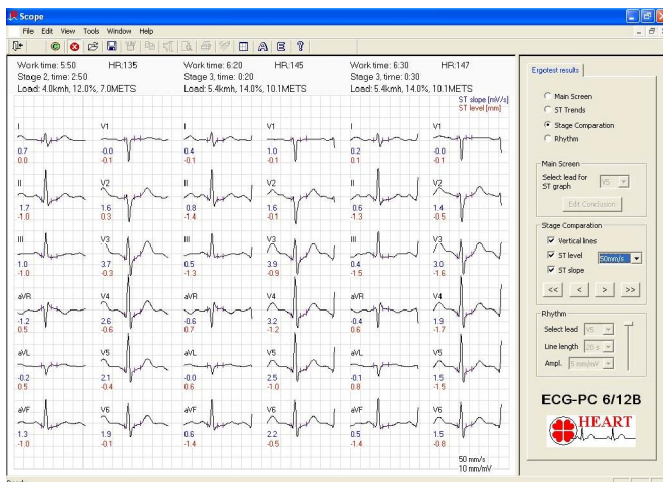


Fig.6 Exercise test results - Stage comparison window

Stage comparison window (Fig.6) displays averaged signals for 12 standard ECG leads, acquired during different stages of exercise test. Also, the ST amplitude and slope values are given beside each ECG signal. Every stage is clearly labeled with name, time stamp, load and heart rate values.

ST trends window shows ST measurement results in a graphical format for every lead with relation to time.

4. VALIDATION

The proposed electrocardiograph has been tested at the Institute „Niška Banja“ in Niška Banja.

The algorithms implemented in the Scope application were especially tested [6]. The results show that the information about waveform shape is very accurate and useful for ECG classification and cardiac diagnosis. The important advantage of proposed system is proved quality of ECG signals and absence of noise and signal drift; even when signals are acquired in the late stages of exercise test with high load values. The measurements of ECG signal parameters obtained using Scope program are comparable in accuracy with those obtained by human experts. The whole exercise test process is successfully managed by the software. Ergo-meter bicycles and treadmills are efficiently and reliably controlled over RS232 port of the PC.



Fig. 7. Novel ECG signal acquisition module for stress testing

5. CONCLUSION

The proposed ECG signal acquisition system consists of external module connected to the PC over the USB port and the software application that runs in Windows OS. The acquisition module is designed to be lightweight and easily portable. The module enclosure's dimensions are only 105x58x18.5mm and weight is only 200g. The communication between PC and module is USB. The module gets the power supply also from USB port.

The software is comprehensive high-end application for stress testing. It has user-friendly graphical interface and many advanced features for recording and analyzing the ECG signals. The electrocardiogram is shown on the PC monitor. The doctor, the user of program, can print recordings and analysis results on printer connected to the PC. Also, the software provides database for ECG recordings storing. The whole exercise test process is controlled by the software. Ergo-meter bicycles and treadmills are digitally controlled over RS232 port of the PC.

The proposed electrocardiograph has been evaluated at the Institute „Niška Banja“ in Niška Banja. The proposed system successfully fulfilled all requirements that modern cardiac stress testing demands.

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