Design And Development Of An Efficient And Cost Effective ECG Simulator Capable Of Generating Normal And Pathological ECG Signals

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***Abstract*— Cardiovascular diseases (CVDs) are one of the major causes of death worldwide According to the publication of World Health Organization (WHO), number of deaths in Pakistan due to cardiovascular diseases (CVDs) reached by 111,367 or 9.87% of total deaths. Pakistan stands at #63 in the world. This shows that the death rate is increasing day by day. For diagnostics and treatment of cardiovascular diseases (CVDs), proper diagnostic and well calibrated equipment is required. The initial test for diagnosing any heart disease is carried out by electrocardiography (ECG). For calibration of such equipments, test equipment is used. ECG simulator is the major equipment used for calibration and testing of ECG machines and Patient Monitors. Currently available ECG Simulators are very costly and microcontroller based, which consists of some specific number of signals that cannot be changed. The idea behind this thesis was to design and develop of a cost effective and customized Arduino based 4-lead ECG Simulator. It was customized in such a way that user can change the number and type of signal, according to the requirement. It will be beneficial for students for their research purpose as well as local manufacturing industry for production of device. Analog ECG signals were burned into arduino Due board. User interface was designed in such a way that user can easily select the required ECG signal and observe it on oscilloscope as well as on serial plotter (by using arduino UNO). This whole designing and working is carried out by using arduino software. The output signals are the combination of limb leads (Right Arm, Left Arm, Right Leg and Left Leg). These waveforms are then verified by using Fast Fourier Transform and cross correlation. The type of signal chosen from the user interface can be observed on Liquid Crystal Display (LCD) and its waveform can be seen on oscilloscope as well as biopac system.**

Keywords: Cardiovascular diseases (CVDs), Electrocardiography (ECG), Arduino UNO, ECG simulator.

I. INTRODUCTION

Cardiovascular diseases (CVDs) are considered as one of the major cause of death globally. According to the publication of World health organization (WHO), number of deaths in Pakistan due to CVDs is reached by 111,367 or 9.87% of total deaths [1]. Pakistan stands at #63 in the world. This shows that the death rate is increasing day by day. By the year 2030, this rate is expected to be increased by 23.6 million.

Electrocardiogram (ECG) signals consist of important source of information for the cardiologists [1]. For diagnostics and treatment of CVDs, proper diagnostic and well calibrated equipment is required. The initial test for diagnosing any heart disease is carried out by ECG. For calibration of such equipment, test equipment is used [13].

ECG simulator is the major equipment used for calibration and testing of ECG machines and Patient Monitors [3]. An ECG simulator is a device used to generate electrical signals similar to human heart electrical signals, which calibrates different ECG machines and patient monitors [12]. It simulates an ECG for cardiac rhythms and is used to check different heart problems. It is usually in the form of a software program and is also available online. Currently available ECG Simulators are very costly and microcontroller based, which consists of some specific number of signals that cannot be changed. Due to the involvement of too much electronic circuitry in pre- existing designs of ECG Simulator, it makes them very difficult and time consuming to troubleshoot [13].

Different designs of ECG simulators have been developed. Some are capable of generating nine ECG signals and a calibrated square wave of 1Hz, 1mV at lead II. An 8-bit microcontroller used along with a direct digital synthesis (DDS) approach, which allows the generation of signals with good quality [4]. An external precision D/A converter and a second order low pass filter used for further smoothening of signals. In this design, samples of ECG waves were organized in the form of look up tables. The program reads the waveform samples step by step in the form of LUT and writes tem into the 8 bit D/A converter (AD557). The program used was in the form of assembly language by using Microchip's MPLAB). A low dropout voltage regulator used to extend the battery life [4]. Different other ECG simulators are based on the mathematical modeling to generate ECG signals. [9], [10], [11].

Another design is a testing device of 12 lead ECG recorders. In this design, normal ECG waveforms of different bpms and a single state of arrhythmia were generated. The outputs of these waveforms were monitored by Atmel ATmega8515 microcontroller. The beat rate was generated by electronic circuit and the amplifier circuit was activated by the microcontroller as a result of the reference voltage at the outputs [13]. This output was then driven by transistors and their conduction lightens up the red LEDs. A 16x2 LCD and push buttons were used for the selection of signals. The microcontroller was programmed by using a C language in Code Vision AVR compiler [5].

The other design is arduino based ECG simulator. It was done by using an arduino UNO board with the help of C programming language. It was actually a 2-lead simulator and signals were acquired online [14]. It was able to generate twelve numbers of signals, including normal, abnormal waveforms, atrial blood pressure, normal resting respiration and hypoventilation. These signals were then fed into the permanent storage of arduino by converting into hexadecimal format, which were then observed by using an oscilloscope. A graphic user interface (GUI) was designed by using push buttons for up/down scroll and for the selection of signals. Moreover, a second order low pass filter was designed in National Instruments (NI) Multisim [6].

Arduino is an open source platform of electronics which is composed of a microcontroller, programming language and an IDE (Integrated Development Environment). It is compatible with Windows, Mac OS X and Linux. It’s software can be used with any arduino board [7].

The Arduino Uno board that is used in this project has a built-in microcontroller with easily accessible ports. It is cheap and readily available. The other board which is used in this project is arduino due board, which consist of built in DAC ports. C is the programming language that is used to build code and upload on the board [8]. Over all, this arrangement may provide a cheap and customizable solution to test and calibrate ECG devices where the users could choose many normal and pathological ECG signals.

II. METHODOLOGY

The block diagram of customized ECG simulator is given below in figure 1:

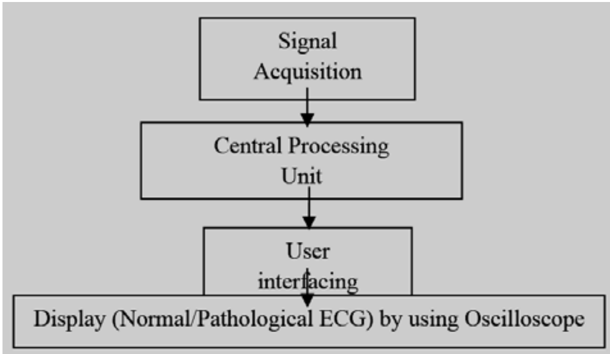

Figure 1: Block Diagram of Custom made ECG Simulator.

A. Signal Acquisition

The first step of the design was to acquire different ECG signals, for every lead (RA, LA, RL w.r.t ground). The left leg (LL) is set as ground terminal. The signals were saved in the form of text files for same number of samples and then normalized according to 12-bits for the processing by using MATLAB software [The Mathworks, MU Guide - Inc., Natick, MA, 1998].

B. Central Processing Unit

The output from Arduino Due is in the form of digital signal. In arduino due, there are two DAC pins, whereas three DAC pins are required for output from each lead. As per the requirements, an additional DAC module i.e. MCP4725 is used as shown in figure 2.

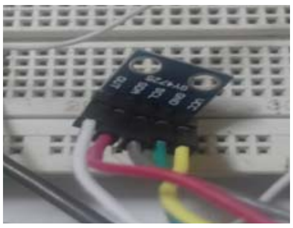

Figure 2: DAC module i.e. MCP4725.

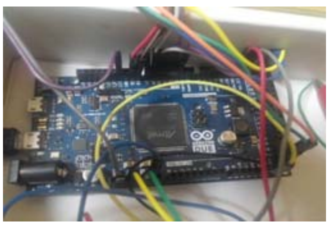

Figure 3: Arduino Due Board.

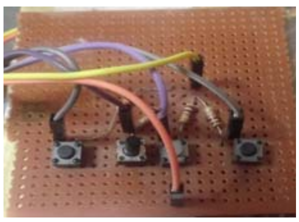

Figure 4: Push Buttons to reset, set, up and down.

Figure 5: LCD output connected with “Up” and “Down” scroll of buttons.

In processing phase, the length of signals is kept same in order to avoid any error. Arduino due board is used because of its built in two DAC pins as shown in figure 3. The signals are saved in the form of a header file, from where the specific signal is selected and send to the output pins as per requirement. A high speed single channel DAC module MCP4725 is used; the third signal is send to this pin as an output [2]. The output signals can be easily seen on the oscilloscope and serial plotter as well. The signals are normalized according to 12-bits before processing.

C. User Interface and Display

A user interface is designed by which a user can interact with the device by means of software. This interaction is carried out by using Liquid crystal display (LCD), which is connected with four push buttons, by which the required signal is selected. Each push button is responsible to perform different tasks. Two push buttons are used for scroll up and down, one is for reset the device and the last one is used to select the signal as shown in the figure 4.

The input is sent by using these input push buttons for the selection of the specific signal, whose names are written on the LCD as shown in figure 5.

After selecting a specific signal, that specific signal will be sent to the output pins of each lead. These signals can also be seen on serial plotter of arduino using laptop and oscilloscope. So, the user can observe signal using two displays i.e. serial plotter and oscilloscope. These signals are then verified further by using Fast Fourier Transform (FFT) and cross correlation.

III. RESULTS AND DISCUSSION

The results of the signals, their Fast Fourier Transforms (FFT) and correlation are discussed below. As the ECG signal is in the range of 0.01 to 300 Hz, sampling frequency is set as 125 Hz.

A. Normal ECG Signal

The output signals of normal ECG for right arm lead along with their FFTs and correlation are given in figure 6. The rest of the leads (LA & RL) persist same behavior.

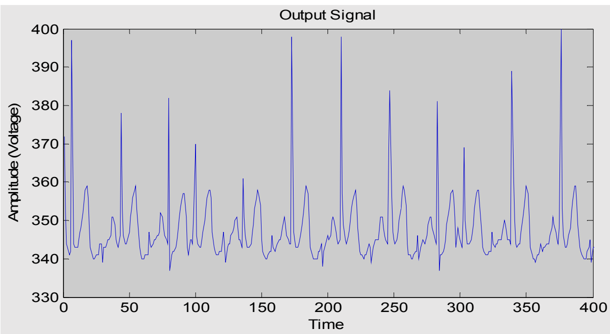

Fig.6-a. Output Signal of Right arm

The number of samples is the same as input signal but the amplitude decreases from the range of 0 mV to 1200 mV to the range of 330mV to 410 mV as shown in figure 6a. These signals are then verified by using FFT and cross correlation of both the signals.

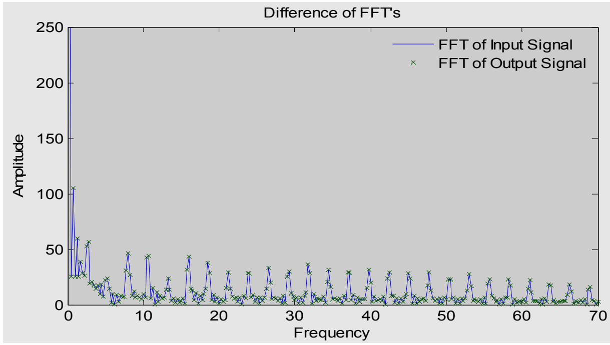

Fig6–b. Fast Fourier Transform.

A linear cross correlation of input and output signal is observed as shown in figure 6c.

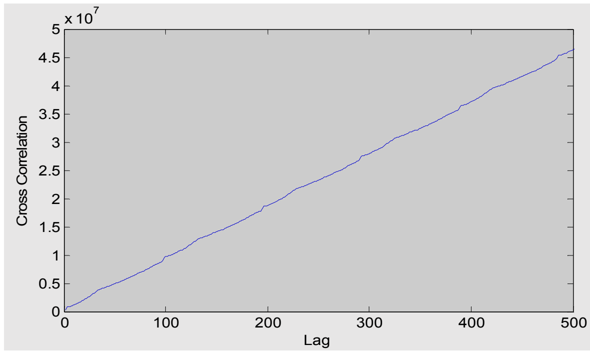

Fig6-c. Cross Correlation

Figure 6: Right Arm a) Output Signal, b) FFT difference of both signals, c) Cross Correlation of input and output signal.

B. Sinus Rhythm 30 BPM

The sinus rhythm, with frequency less than 60 bpm is usually known as bradycardia. The other leads show the same response as right arm. The output arising from the controller ranges from 330 to 400 mV as shown in figure 7a.

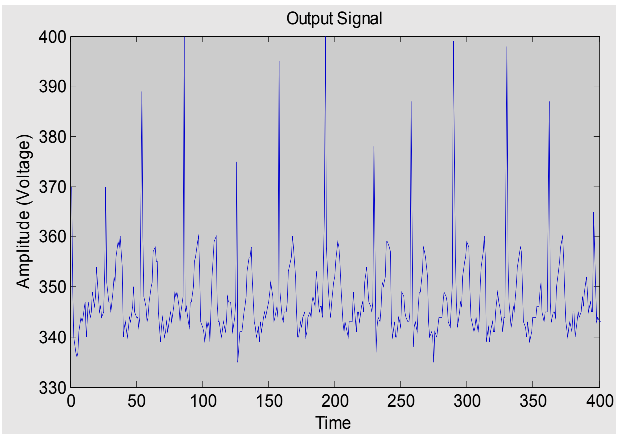

Fig.7-a. Output Signal of Right arm

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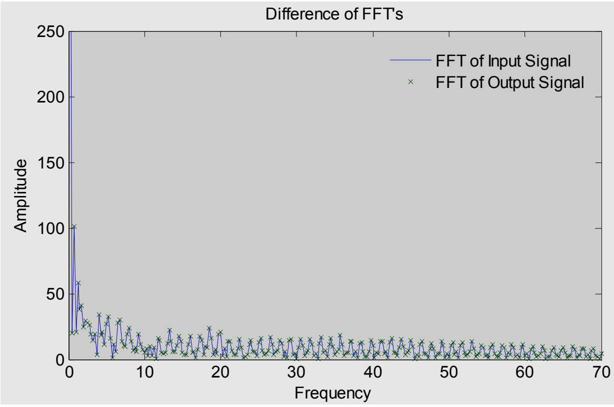

Fig.7-b Fast Fourier Transform

When the signal is further verified by taking FFTs, same peaks has been observed as shown in the figure 7b.

Correlation of these signals is linear and its response is towards positive axis.

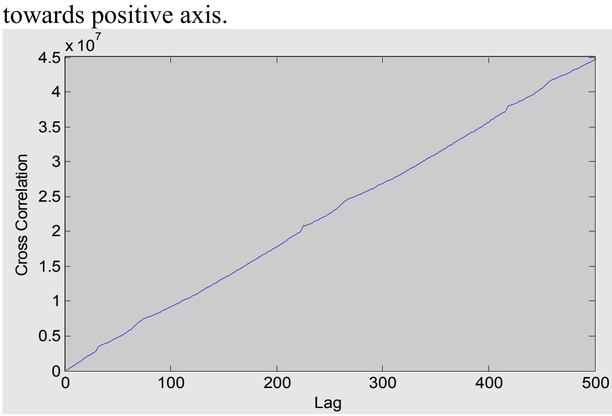

Fig.7-c. Cross Correlation.

Figure 7: Right Arm a) Output Signal, b) FFT difference of both signals, c) Cross Correlation of input and output signal.

C. Sinus Rhythm 90 BPM

The sinus rhythms greater than 60 bpm are known as tachycardia. The output signal of right arm along with FFT and correlation of Sinus rhythm 90 bpm are shown in figure8. Similarly, the other leads show the same response as right arm.

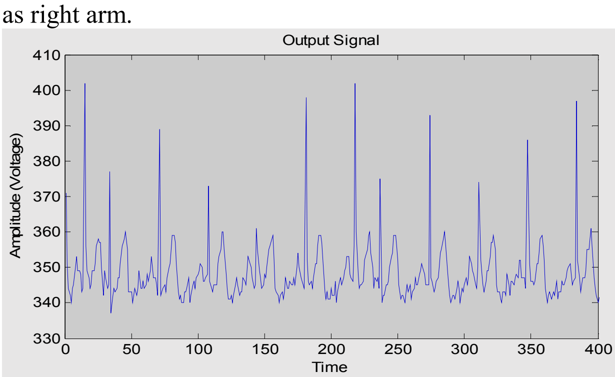

Fig.8-a. Output Signal of Right Arm

The amplitude of the output signal is in the range of 330 to 400 mV. The FFT of the signals shows the same number of prominent peaks.

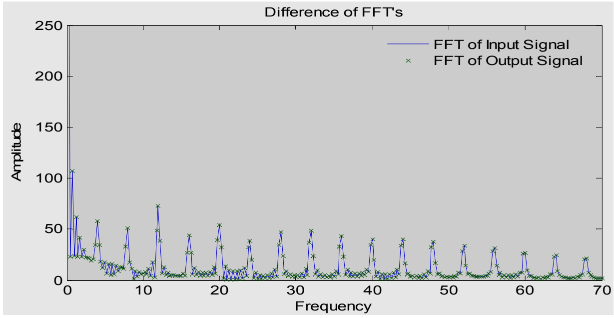

Fig.8-b. Fast Fourier Transform (FFT)

A smooth and linear curve is observed in the cross correlation of the signals in figure 8c.

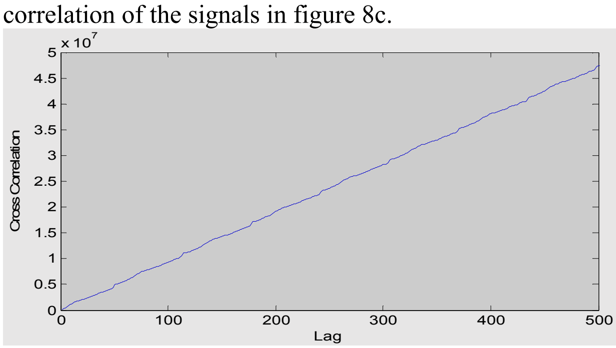

Fig.8-c. Cross Correlation.

Figure 8: Right Arm, a) Output Signal, b) FFT difference of both signals, c) Cross Correlation of input and output signal.

D. Atrial Flutter

The atrial flutter is normally characterized by P waves. P wave is in the form of ripples and is very hard to distinguish. The amplitude of the output signal is in the range of 160 to 280 mV.

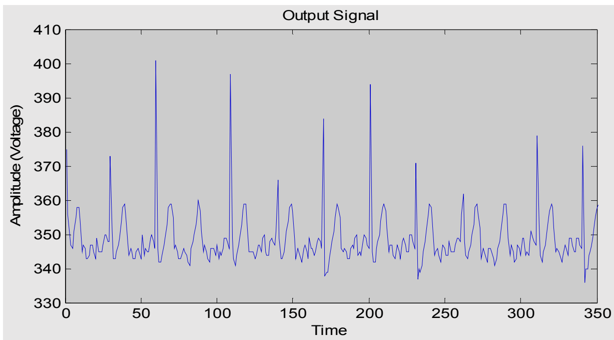

Fig.9-a. Output Signal of Right Arm.

Same peaks are found for both signals and linear positive correlation has been observed.

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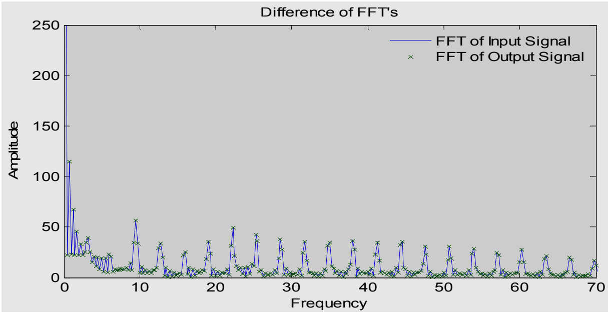


Fig.9-b. Fast Fourier Transform (FFT)

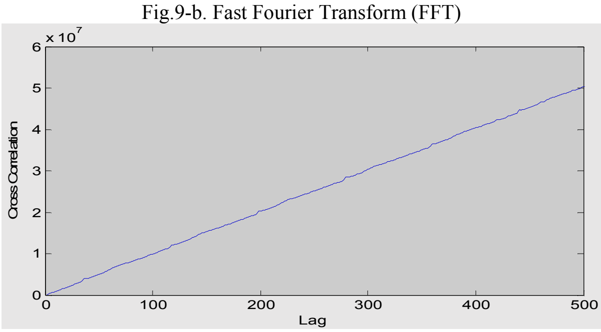


Fig.9-c. Cross Correlation.

Figure 9: Right Arm, a) Output Signal, b) FFT difference of both signals, c) Cross Correlation of input and output signal.

E. Ventricular Fibrillation

In this signal, P wave is usually absent, QRS complex is not very clear and the waveform is just like a series of wavy lines. The output signal is under the range of 330 to 415 mV.

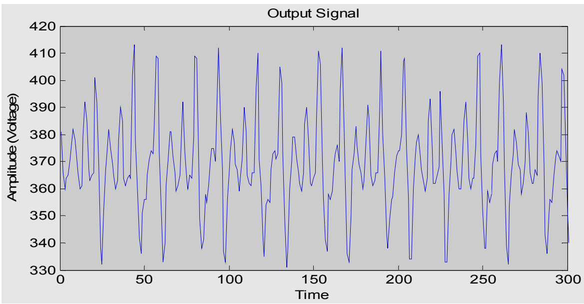


Fig.10-a. Output Signal of Right Arm.

The FFTs shows some random peaks which are high in amplitude at some points, from 40 to 55 Hz very small peaks are observed as shown in figure 10b.

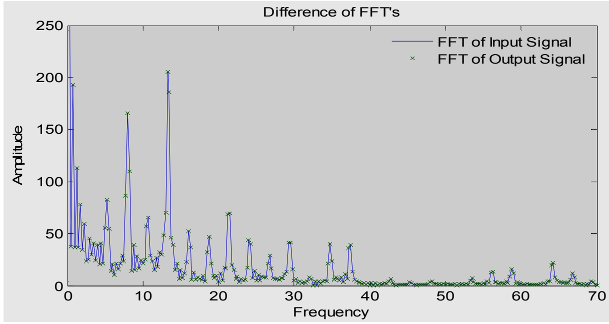


Fig.10-b. Fast Fourier Transform (FFT)

Correlation of these signals shows positive behavior with small curves at some points as shown in figure 10c.

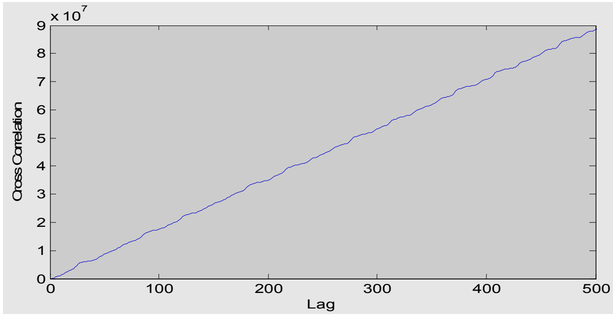


Fig.10–c. Cross Correlation of input and output signal.

Figure 10: Right arm, a) Output Signal, b) FFT difference of both signals, c) Cross Correlation of input and output signal.

F. Sinus Arrhythmia

In sinus arrhythmia, irregular rhythm is observed. This irregularity of rhythm varies with the respiratory cycle. The output signal is in the range of 330 to 400 mV, with some variation in the QRS complex.

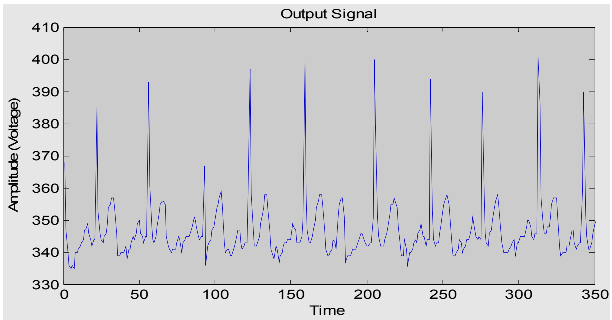


Fig.11-a. Output Signal of Right Arm.

The FFTs shows no difference in between the input and output signals. Both signals share same number of peaks at same points as shown in figure 11b.

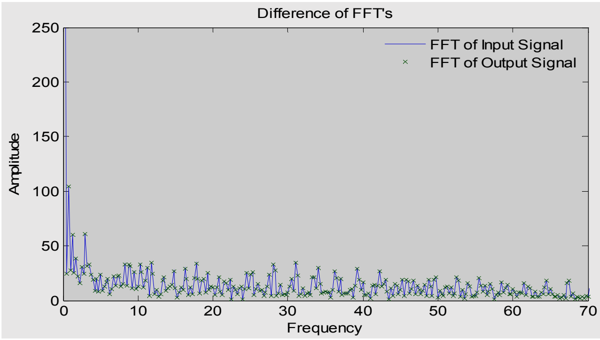


Fig.11–b. Fast Fourier Transform (FFT).

Similarly, correlation graph is linear and shows positive behavior of the two signals as shown in figure 11c.

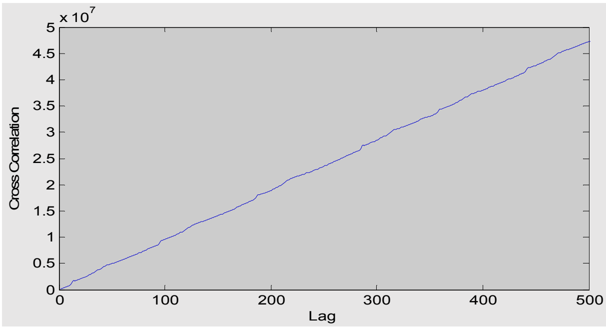


Fig.11-c. Cross Correlation.

Figure 11: Right arm a) Output Signal, b) FFT difference of both signals, c) Cross Correlation of input and output signal.

G. Supra Ventricular Tachycardia

In this pathology, P and T waves show abnormal behavior. Sometimes, P wave is hidden in the previous T wave, and T wave is also distorted as shown below.

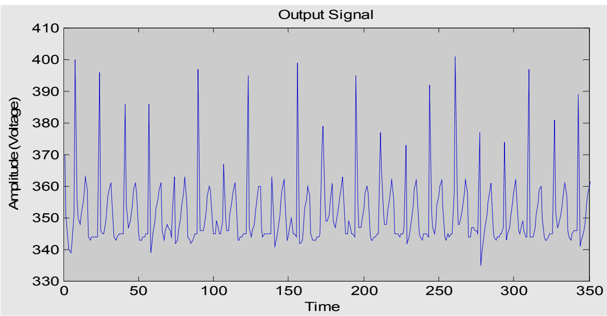


Fig.12-a. Output Signal of Right Arm.

The same number of peaks of both signals can be observed in the FFT. The peaks are very sharp, clear and within the range of 115 db as shown in figure 12b.

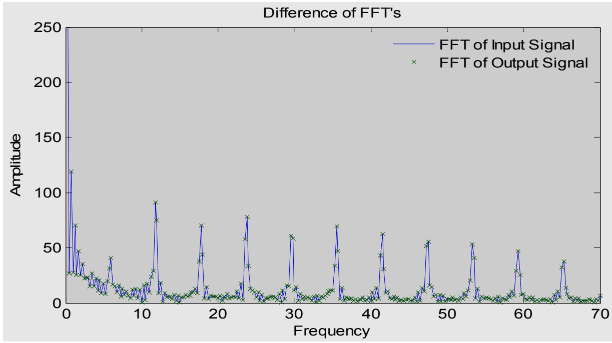


Fig.12-b. Fast Fourier Transform (FFT)

Similarly, the positive correlation is been observed in between the two signals as shown in figure 12c.

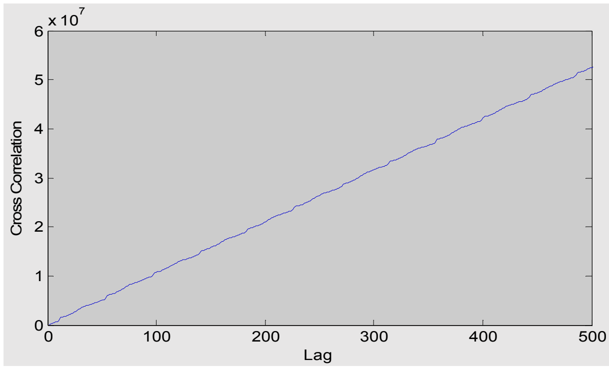


Fig.12-c. Cross Correlation

Figure 12: Right arm, a) Output Signal, b) FFT difference of both signals, c) Cross Correlation of input and output signal.

These signals are then tested and analyzed by using biopac system. This system acts as ECG machine which consists of preamplifiers and several filters for signal conditioning. These outputs show that this ECG simulator can be used to calibrate different ECG machines and patient monitors held at different hospitals without consuming much cost. The results after using biopac system are given in figure 13.

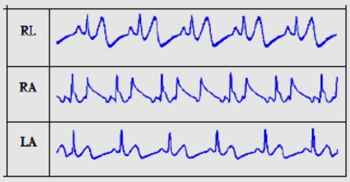
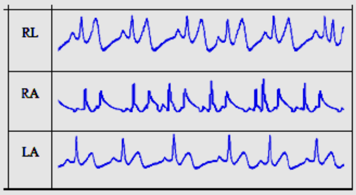
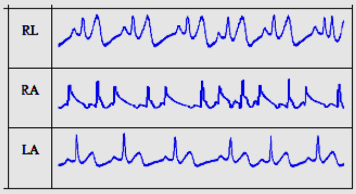
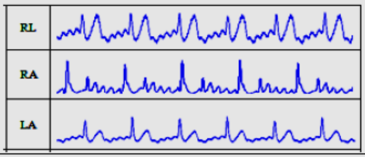
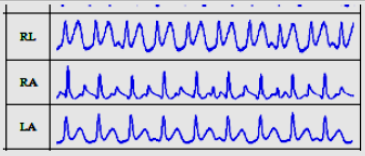
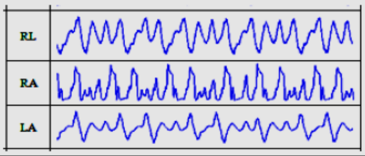
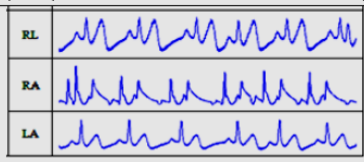
No. of Signal	Signal Name	Biopac output signal
1	Sinus Rhythm 60BPM	
2	Sinus Rhythm 30BPM	
3	Sinus Rhythm 90BPM	
4	Arterial Flutter	
5	Supra Ventricular Tachycardia (SVT)	
6	Ventricular Fibrillation	
7	Sinus Arrhythmia	

Figure 13: Output Signals from BIOPAC.

IV. CONCLUSIONS

In this research, a 4-lead ECG Simulator has been designed and developed. Signals were recorded, which were then analyzed further. The developed device has the ability to test or to calibrate the patient monitors and other ECG machines. It is also very convenient to use for the learning purpose of medical and engineering students. Furthermore, this design is not only cost effective, portable, and accurate but can be customized according to the requirement of a doctor. Future design changes would include a 12-lead system that can be designed in the same way and the resultsof this system can be cross verified by the 4-lead system. More number of signals can be added as per requirement.

The current design is currently USB powered and does not include any battery. The future design change would include a better means of power as well as a proper select button for each time selection of waveforms.

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