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Design and Prototype of a Biosignal Simulator

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Abstract

The proposed work is based on the design and development of a low-cost biosignal (ECG) simulator by artificially constructing standard ECG signal along with multiple arrhythmias that include Brugada syndrome which is considered to be one of the rarest and not present in simulators available in the market. Since Cardiovascular malady is one of the prime causes of death in developed countries, the electrocardiograph (ECG) instrument is considered to be a significant diagnostic device available in the medical field. A standard electrocardiogram consists of the P wave, PR interval, QRS complex, ST segment, T wave, QT interval, and U wave. Therefore minute variation in these waves, result in cardiac disorders. By using an ECG simulator, the vital signs of the heart can be simulated to test the equipment before using it in contact with the patient. Typical simulators available in the market make use of stored ECG signals. Therefore, this article examines the construction of ECG signals without storing data using Processing 3 software and Atmega 328P microcontroller.

Keywords: *Biosignal, Diagnostic devices, ECG generation, Electrocardiograph, Simulator*

I. INTRODUCTION

A biosignal is any signal that is obtained from living beings which can be continuously measured and monitored. Such bio-signals are namely Electrocardiogram (ECG), Electroencephalogram (EEG), Surface Electromyogram (SEMG), Bioacoustic signals (lung, heart, and bowel sounds), Magneto cardiogram (MCG) etc [1]. Bio-signals help in creating communication between the biosystems and is a major source of information for the diagnosis of various kinds of diseases. All these bio-signals are carried out by some sort of energy which can be measured directly from the biological origin, but often external energy is used to measure the interaction between the external energy and the physiological systems [2]. The measured bio-signal should be converted to an electrical signal for which bio-transducers are used. Bio-transducers convert these analog signals attained from these living beings to digital signals which helps in the processing of these signals. Even though magnetic biosignals provide better accuracy than the electrical biosignals, it's not a feasible method because it is quite expensive and also it is sensitive to metals [3]. So electrical signals are used for diagnosis purposes.

Electrical biosignal refers to a change in the electric current generated by the sum total of all the electrical potential differences across various specialized tissues and organs [4]. Since cardiovascular malady is one of the significant root of impermanence among emergent societies, this work concentrates on designing and modeling of biosignal simulator based on ECG and the various arrhythmias linked with it. According to research on this field, simulators designed previously make use of ECG signal data from various sources like hospitals and online databases which causes limitations in adjusting the amplitude and frequency of the signals [5-8]. So our main aim is to develop
a simulator that does not make use of recorded data, instead construct each electrocardiogram signal and its various
abnormalities which removes amplitude and frequency limitations.
ECG or EKG refers to the electrical activity of the heart i.e. an electrical impulse will progress through the heart which founts the heart muscle to clutch and

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pumps blood from the heart. ECG is taken to detect abnormal heartbeat which may have caused due to blood clots. Various heart problems such as coronary artery occlusion, areas of the vandalized heart muscle, enlargement of heart etc. can be detected by taking Electrocardiogram [9].

Fig.1. represents the basic ECG wave. ECG consists of three main components i.e. P wave, QRS complex and T wave.

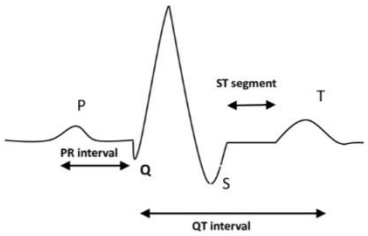

Fig 1.Electrocardiogram

The P wave is an important wave that depicts the depolarization of left and right atria that result in contraction of atria or atrial systole. Duration and amplitude of the P wave is 0.12 sec and 2.5mm.

The PR interval is the time from the outset of the P wave to the beginning of the QRS complex. Conduction of the AV node is reflected by the PR interval. A typical PR interval ranges between 120-200ms (0.12-0.20s). If the interval is greater than 200ms, the heart block is said to be present.

QRS wave renders the activation of the left and right ventricles i.e. ventricular depolarization. The duration of the QRS complex is 0.10 sec and the amplitude differ from person to person and lead to lead .The voltages depend on the size of the ventricular chambers and the closeness of the chest electrodes to ventricular chamber i.e. the closer the electrode, higher the QRS voltage.

ST-segment is an isoelectric and flat region of ECG wave that connects the end of S wave which is also known as junction point or J point and the starting of T wave. Therefore the ST segment represents an interval that lies between ventricular depolarization and repolarization. The duration of ST-segment is typically 0.08sec.

T wave in ECG denotes the repolarization of ventricles. It represents the starting of the QRS complex to the tip of T wave which is also mooted to as an absolute refractory period. The duration of the T wave is 0.10 to 0.25 seconds and amplitude is less than 5mm.

II. ARRHYTHMIAS

Arrhythmia is also known as irregular rate or improper rhythm of heartbeat [10]. It is classified based on the rates at which heart beats and the site of origin. Based on heart rate, it is of two types i.e. Bradycardia and Tachycardia [11]. If the heart beats too slowly then it is called bradycardia (less than 60). When the heart beats faster, then it is known as tachycardia(greater than 100) and based on the site of origin, it is of different types such as atrial arrhythmia, junctional arrhythmia, ventricular arrhythmia, and heart block [12].

1. Premature Atrial contractions

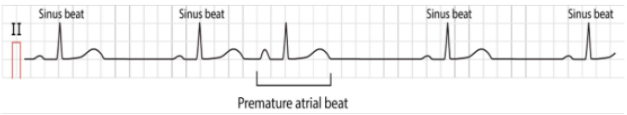

Fig .2. Premature Atrial Contractions
Source: Adapted from [9]

As per Fig .2., Premature atrial contractions (PACs) ensue from ectopic pacemaker cells positioned in the atrium. A P wave betides abnormally before the envisage cardiac cycle [13]. This P wave may or may not be progressed through the AV node. The amplitude of the P wave is slightly higher than that of a normal P wave. The QRS complex appears to be normal. The heart rate is between (60-80bpm).

2. Atrial Fibrillation

Fig .3. Atrial Fibrillation
Source : Adapted from [9]

Atrial fibrillation [fig.3.] is detected in ECG when there is a lack of P wave at the beginning of a normal heartbeat. Fibrillatory waves with varying size, timing and shapes are produced due to rapid oscillation of heart which is also termed as F waves [14]. Smaller the F wave, then it is called fine fibrillatory wave and larger the wave, coarse fibrillatory wave. Atrial fibrillation is caused due to rapid atrial rhythm (400-600bpm) which is originated from atria. The P wave may or may not be present. F waves can be observed instead of the P wave.

3. Atrial Flutter

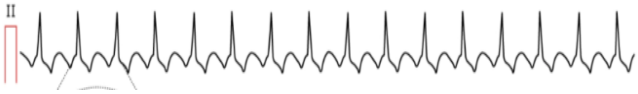

Fig. 4. Atrial Flutter
Source: Adapted from [9]

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During atrial flutter [fig.4], electrical activity produced in atria is coordinated therefore, atria contracts at a very rapid rate i.e. 300bpm. These rapid contractions can be observed on ECG as flutter waves. These waves are very broad and appear as saw toothed [15].

4. **Long Q-T Syndrome**

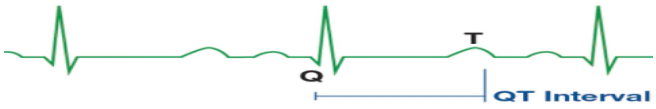

Fig .5. Long Q-T Syndrome
Source: Adapted from [30]

Long QT syndrome [fig.5.] is a sporadic heart condition where there is a delay in repolarization of ventricles which cause longer QTc (greater than 0.44s) intervals on ECG. The frequency of heartbeat is much rapid and chaotic which causes sudden death [16, 17].

5. Ventricular Tachycardia

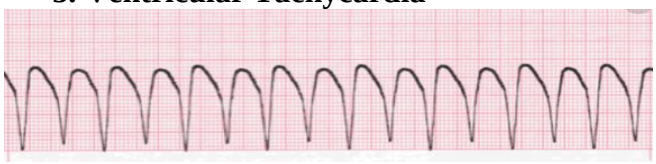

Fig .6. Ventricular Tachycardia
Source: Adapted from [29]

During ventricular tachycardia [fig.6.], the rate of heartbeat is extremely high (greater than 120bpm) which arises from one of the ventricles. Ventricular tachycardia can lead to ventricular fibrillation and cause death. QRS duration during ventricular tachycardia is greater than 0.12s [18].

6. Ventricular Fibrillation

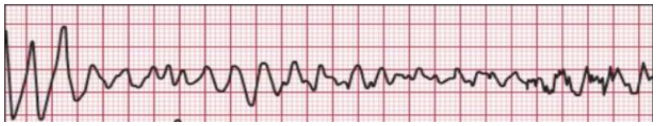

Fig .7. Ventricular Fibrillation
Source: Adapted from [29]

During ventricular fibrillation [fig.7.], the ventricles tries to contract at the rates greater than 300bpm [19]. There is no P wave present and the ECG wave is more like a fibrillatory baseline signal.

1. Premature Ventricular Contractions

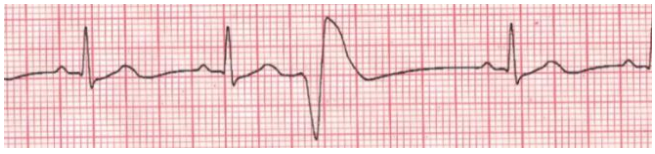

Fig .8. Premature Ventricular Contractions
Source: adapted from [29]

In the caseof Premature Ventricular contractions [fig.8.] , a series of abnormal heartbeats occur from the ventricles or lower chambers of the heart during a regular heartbeat. HR is between 60-80bpm [20].

2. AV Nodal Reentrant Tachycardia

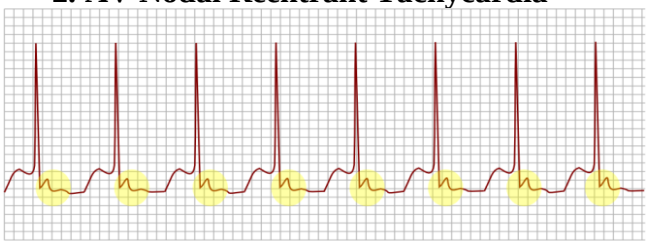

Fig .9. AV Nodal Reentrant Tachycardia
Source: adapted from [30]

AVNRT [fig.9.] is one of the rifest types of super ventricular tachycardia (SVT). It is an abnormally abrupt heart rhythm that emanates from a place above the bundle of His. HR is between 140-280bpm [21]. In most cases, P wave is embedded in the QRS complex or occurs right after the QRS complex.

3. Junctional Rhythm

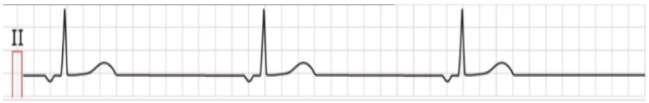

Fig.10. Junctional Rhythm
Source: adapted from [9]

As per fig.10, a junctional rhythm is produced when there is an emergence of electrical activity of heart within or near the AV node rather than SA node [22]. The morphology of the QRS complex is similar to that of the regular sinus rhythm, whereas the P wave is absent or retrograde P wave occurs after the QRS complex. The rhythm can be slower (less than 40bpm) or rapid (greater than 100bpm), based on that it is called junctional bradycardia or tachycardia.

4. Brugada Syndrome

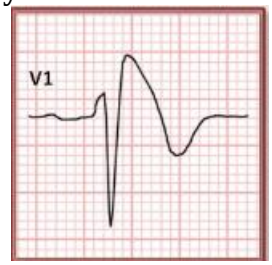

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Fig .11. Brugada Syndrome
Source: adapted from [29]

Brugada syndrome [fig.11] is a rare genetic arrhythmia caused due to mutation in the sodium channel. This ECG pattern consists of a coved type ST-segment which is elevated greater than 2mm [23]. It has broad P wave with prolonged PQ and a negative T wave.

5. Wolff Parkinson White Syndrome

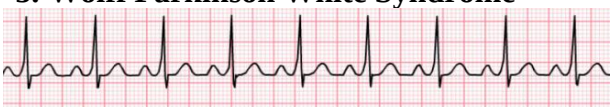

Fig .12. Wolff Parkinson White Syndrome
Source: adapted from [29]

Wolff Parkinson White Syndrome (WPWS) is the sole ventricular pre-excitation. The ECG of WPW consists of a PR interval shorter than the standard ECG signal and the delta wave. A delta wave is a mumble upward movement of QRS complex. Therefore, QRS wave occurs as soon as the P wave, thus making it a delta wave [24].

6. Heart Block

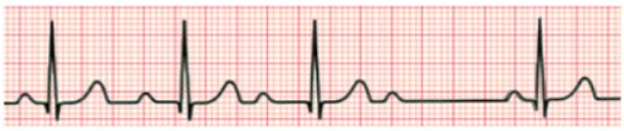

Fig.13. Heart Block
Source: adapted from [29]

Fig.13 denotes the Heart block or AV block which is an abnormal heart rhythm caused due to slow (bradycardia) beating of heart i.e. the electrical signals that help in contraction are partially or fully blocked between atria and ventricles [25].
According to various existing laws, all the medical equipments which possess direct contact with patients must be tested for safety. The parameters that are used for measurement should also be tested in order to obtain accurate results while making use of the device[26].Therefore, preponderance of medical device require a simulator to analyze their rate of performance. ECG simulator is the most requisite device used for testing equipments which intake ECG signals. The vital signals of the heart can be simulated using this device which in turn eliminates the defects of ECG. This ECG simulator can generate wide varieties of arrhythmias including one of the rarest irregularities caused due to genetic mutation known as Brugada syndrome.

III. MATERIALS AND METHOD

An ECG signal of a healthy individual constitutes various spikes and waves. So the primary pattern and corresponding timings change with heart rate. The early conceptual design of the simulator is done based on digital implementation which is carried out using processing 3 software. Based on the design developed, Atmega 328P is made use of inorder to artificially construct the ECG wave by splitting up the wave into different parts. P, QRS Complex, T waves are generated separately and combined to form the standard ECG signal [27, 28]. Since each component is separately generated, there is no storing of ECG signals which is a common method used in simulators available.

Based on the initial construction of a standard electrocardiogram signal, arrhythmias have been derived from the constructed standard ECG waveform.
Initial construction of the ECG waveform was done in processing 3 software where the P wave is generated using:

$$x(t)=A*\text{Sin}\theta \quad (1)$$

where, A- Amplitude of the signal

A positive half cycle of a sine wave is considered with a duration of 0.12-0.20s and amplitude of 0.25mV.

QRS Complex is generated by constructing a line and creating a bend to form a slope of ramp wave with a particular amplitude using:

$$y = A*(\text{mod}(x - BP)) - SF \quad (2)$$

where, A is the amplitude
BF - Bending point
SF- Shifting factor

PQ interval and ST junction is constructed using :

$$y= ax+b ; \quad (3)$$

where a- Slope of the line
b- intercept

T wave is generated using another positive cycle of a sine wave with an amplitude higher than P wave with a duration of 0.08s and amplitude of 0.4 mV.

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All the arrhythmias are generated by modifying above mentioned equations based on bending points, shifting factor, the slope of the line and amplitude.

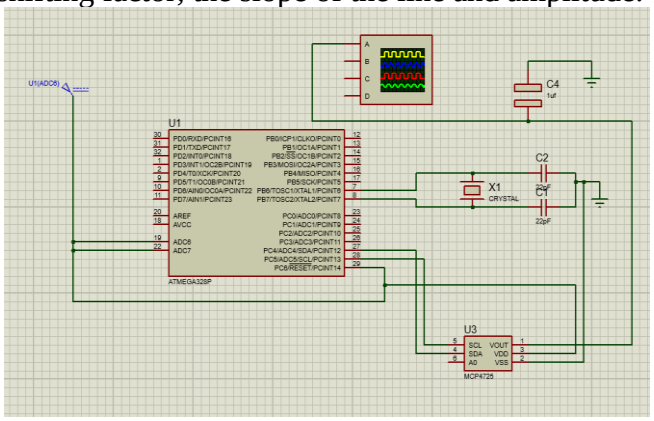

Fig.14. Schematic Circuit Diagram of ECG Simulator

According to the schematic circuit of this device rendered in figure 14., a 5V DC is given as the supply voltage to ATmega 328P. MCP4725 is a digital to analog converter which is connected to the ADC pin of the microcontroller. Capacitor C4 is used to smoothen the generated QRS complex. The electrocardiogram signal is obtained on the Vout pin of MCP4725.

IV. RESULTS AND DISCUSSION

The size of the Processing 3 screen dimension is considered
to be [1900x1080].
First, the signals are generated in processing 3 software and then a schematic circuit is built using Atmega 328P microcontroller on Proteus 8 professional Software. Then breadboard level implementation is done based on the schematics done on Proteus, where the signal is displayed on an oscilloscope. All the signals constructed using processing 3 software is of 0.7hz [figure 17], 1hz [figures 18- 27], 2hz [figures 28, 30] for a better output signal display. The frequency can be changed further based on different arrhythmias.

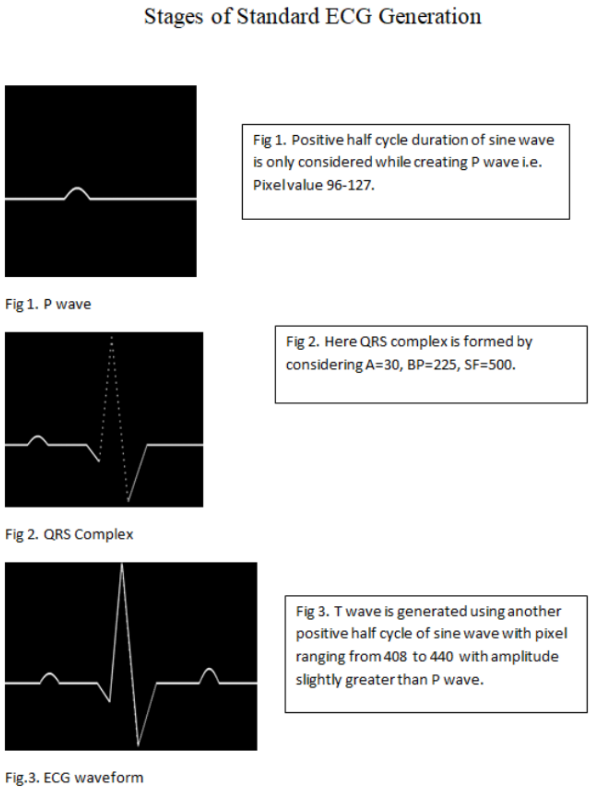

Fig .14. Stages of standard ECG construction

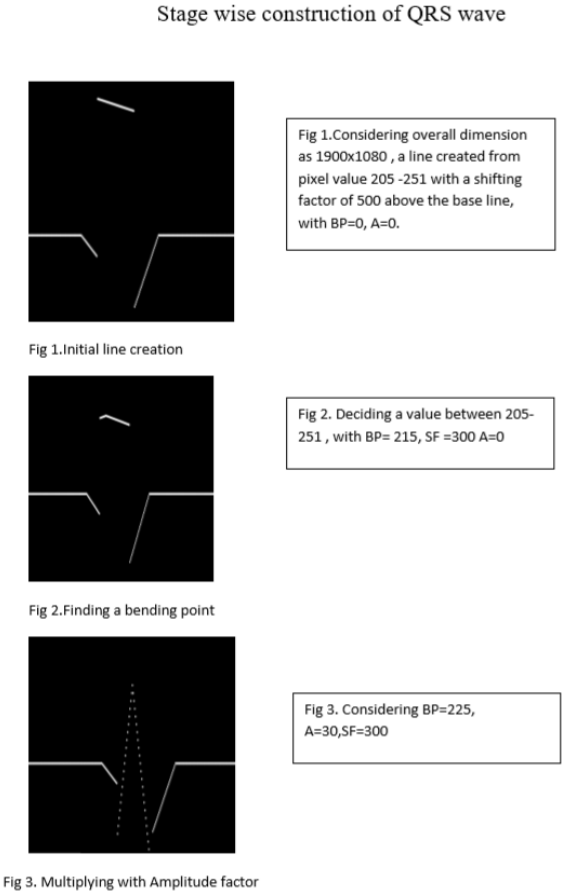

Fig.15. Stage wise construction of QRS Complex

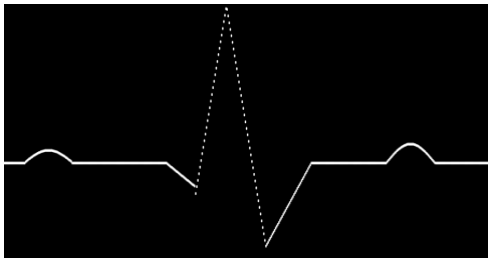

Fig .15. Bradycardia

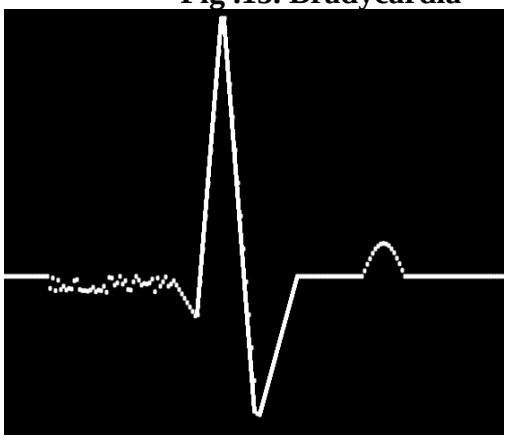

Fig.16. Atrial Fibrillation

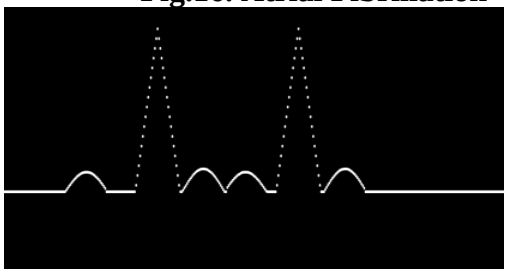

Fig .17. Atrial Flutter

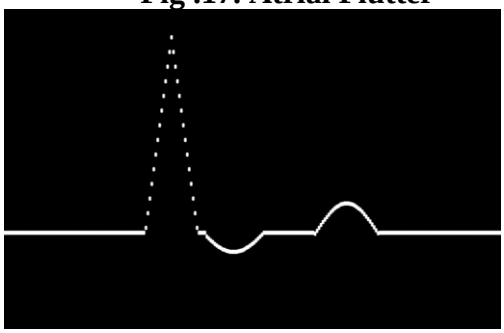

Fig. 18. AV Nodal Reentrant Tachycardia

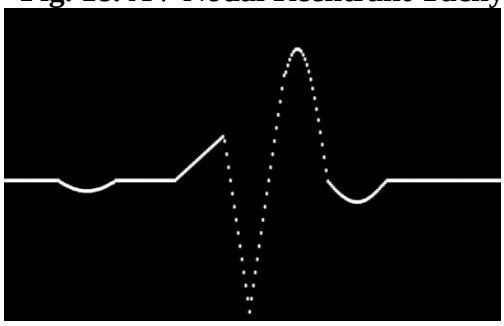

Fig .19. Brugada Syndrome

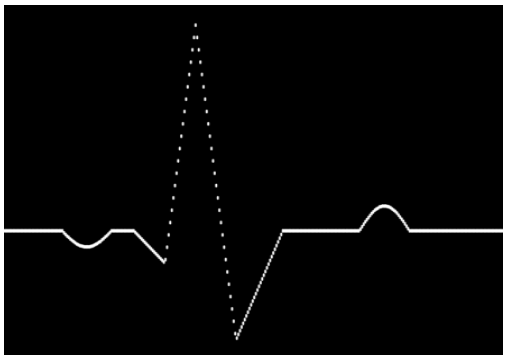

Fig .20. Junctional Rhythm

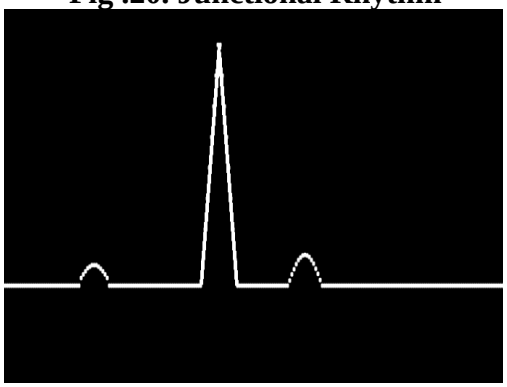

Fig.21.Premature Atrial Contractions

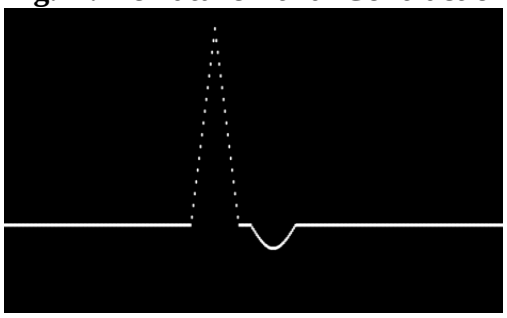

Fig.22.Premature Ventricular Contraction

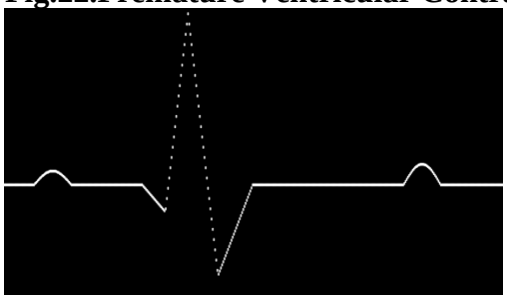

Fig .23. Long Q-T Syndrome

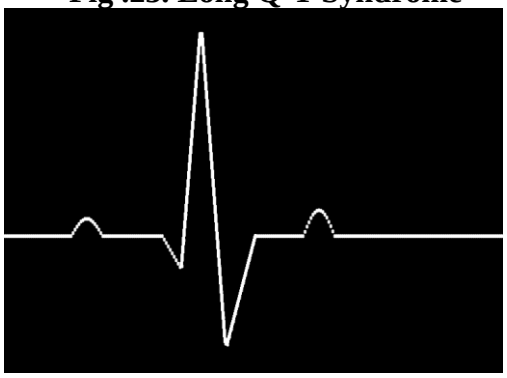

Fig .24.Tachycardia

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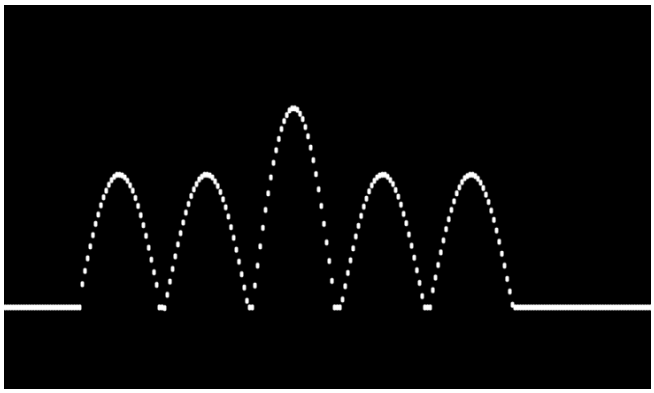

Fig. 25. Ventricular Tachycardia

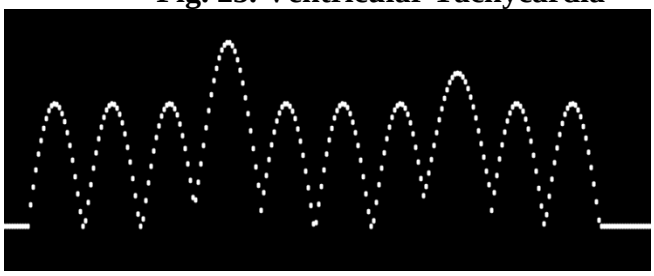

Fig.26.Ventricular Fibrillation

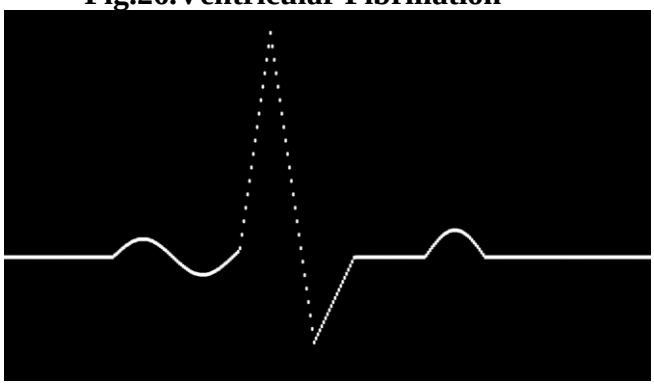

Fig .27. Wolff Parkinson White Syndrome

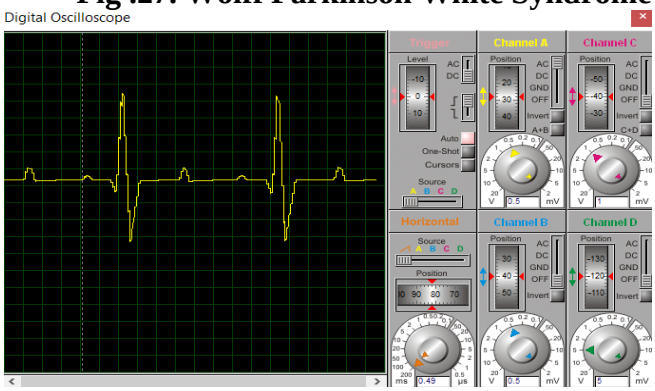

Fig 29. ECG Signal obtained using ATMEGA328P

Small square method can be used to determine the heart rate based on the signal obtained on an oscilloscope. This approach stated in this paper can be used to simulate the accuracy and feed the data to Deep Learning techniques to classify ECG arrhythmias [31] and can be extended to modeling of fetal ECG [32] and even further exploration can be done in modeling of BCG waveform [33].

V. CONCLUSION

The fundamental focus of this work is to develop an efficient bio signal (ECG) simulator of extremely low cost which is capable of simulating signals for testing purposes. This tester is capable of simulating ECG signal and various arrhythmias including rare arrhythmia such as Brugada syndrome which is not commonly found in simulators available. Since all the simulators use stored ECG data to test machines, this proposed simulator generates artificially constructed ECG signal based on the electrical characteristics of each signal. Therefore, the signal generated does not possess any amplitude or frequency limitations.

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