Cardiac Output Measurement Using Ballistocardiogram

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***Abstract*— *Ballistocardiogram* (BCG) is a non-invasive technique to measure cardiac parameters. It was popularized by Dr. Isaac Staar in 1940. The *Ballistocardiogram* signal is generated due to the vibrational activity of the heart. BCG was considered as a promising technique but was replaced by *Electrocardiogram* due to the difficulty involved in detecting and analysing the BCG waveforms. With the increase in processing power and better signal processing techniques over the last few decades, BCG has regained its prominence and is being considered to be used as a continuous patient monitoring system. The usability of BCG was limited in the earlier days due to the large size of the equipment and the lack of signal processing systems to analyse this complicated signal. *Cardiac output* is defined as the amount of blood pumped out by the heart in a minute. This parameter can be utilized to determine the state of the heart. One method to determine the cardiac output from BCG waveform has been discussed in section II of this paper. The sensor used for our experiment is a lightweight and flexible sheet type *electromechanical film* which is placed on the seat of the chair. The setup used has a two-stage amplifier which is connected to a data acquisition card which is in turn connected to a laptop. The signal processing is done using NI's software LabView. The BCG setup was made and the signal was successfully validated with ECG. The R-J interval, which is the interval between the R peak of the ECG signal and J peak of the BCG signal, was determined. *Echocardiogram*, another cardiac measurement instrument, was kept as a standard basis for determining the *cardiac output* from the BCG signal. Recording of 14 different subjects have been taken and the *cardiac output* has been determined for each case.**

Keywords— ***Ballistocardiogram, Electrocardiogram, Cardiac Output, Electromechanical film.***

I. INTRODUCTION

BCG or Ballistocardiograph is a recording of the movements of the body caused due to the vibration when blood flows in the arteries [1,2]. A ballistocardiograph measures the motions of the body produced by cardiac contraction. In 1877, Gordon recorded ballistic displacements of the body by placing a subject on a bed suspended by ropes from the ceiling and obtained a record of its motion synchronously with the patient's heart beat. This device was impractical, as the movement of the ballistocardiographic bed caused by respiration was much higher than that caused by the movement of blood [2].

Ballistocardiogram, introduced in November, 1939 by Dr. Isaac Starr and Dr. Henry Schroeder,is a non-invasive technique with which the cardiac output of the human heart can be determined. Ballistocardiography was discontinued due to the lack of sufficient analysis equipment. Electrocardiogram (ECG) was instead used to monitor cardiac activity. Now, with advancement in technology, it is possible to analyze the BCG data. In high frequency BCG [1], the natural frequency of the measurement device was greater than 10 Hz. As the high frequency was so strongly coupled to the surroundings, it did not synchronize with the movement of the body lying on it. Another problem was the natural frequency of the system, which was within the frequency range of the BCG causing distortion in the BCG waveform. Finally, it was obvious that in the Starr 'high frequency' system, information regarding circulation of blood function was seriously distorted, mainly due to the way in which the body was supported. Therefore the bed supporting the patient had to be very light. Since the start, noise has been a major factor and since the measurement is of minute vibrations of the body it has always been a challenge to isolate the heart signal without having a probe or an invasive instrument to measure the vibrations of the heart. The measurement was taken on subject lying in supine position on an observation table. This method of finding the cardiac output was later discontinued due to the difficulties in calculation of the cardiac output.

With development in computation and analysis, it is now possible to determine the cardiac output from a ballistocardiograph. One of the profound advantages of BCG is that cardiac output can be non-invasively measured which in turn is advantageous for predicting the heart behavior.

A typical BCG lags ECG by about 0.1-0.3 seconds. The BCG signal is generated by the movement of heart and blood. When there is a sudden motion of blood mass in one direction, it produces recoil of body in the opposite direction. The BCG measures this recoil with force or acceleration sensors in a sitting or supine position. Major motion of the body is in longitudinal direction along the axis parallel to the spine.

The waveform of Ballistocardiogram is divided into three groups: Pre-ejection, ejection and the diastolic portion of the heart cycle [4]. Pre-ejection (GH) waves consist of the venous return to the heart, atrial filling, and contraction. 'H' represents head-ward deflection, 'I' foot-ward deflection (reflects the rapid acceleration of blood in the ascending ao-

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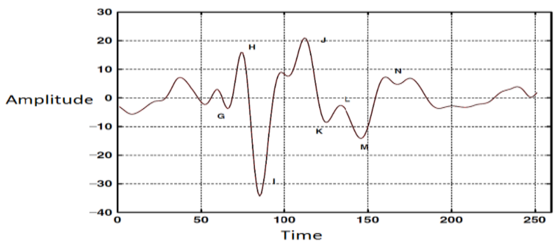

Fig 1: A Typical BCG Curve

rta and pulmonary arteries around the aortic arch and into the carotid arteries.) The ejection phase J-wave describes the acceleration of blood in the abdominal area and deceleration of blood in the head-ward aorta as in Fig 1.

The peak of the J-wave corresponds to the end of rapid ejection of both ventricles. I-J amplitude reflects the force of contraction of the left ventricle and I-J period reflects contractility. The K and L waves reflect the deceleration and cessation of blood flow and the closing of the aortic valve [4]. Diastolic waves (KL and MN) reflect the state of peripheral circulation. Also, the influence of arteries wall stiffness and peripheral resistance has greater influence on the diastolic waves [5].

The sensor that has been used i.e. Electromechanical film is a thin polypropylene film having a special cellular structure. The internal cellular structure is made by stretching the polypropylene film during manufacturing both in longitudinal and transversal directions [8]. The film is charged by corona discharge method using electric field strength exceeding locally the film dielectric strength [6]. While charging the EMFi, the corona charging produces an inhomogeneous surface charge in the case of local breakdown events in the foil. This is also been noticed to be the basis of the EMFi's effective operation [7]. When charging electric field strength strong enough to cause internal electrical breakdown occurs inside the film, the sensor becomes sensitive. Finally the film is metallized on both sides to provide electrodes [8].

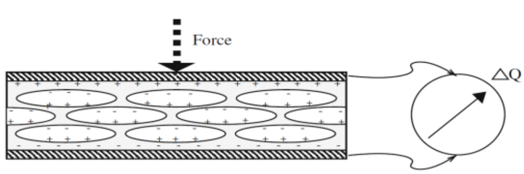

Fig 2: A schematic representation of the EMFi sensor .

The EMFi material is sensitive to dynamic forces exerted normal to its surface. It consists of three layers: 2 layers of smooth and homogeneous surface layers and a dominant, thicker midsection. The midsection is full of flat, air filler voids separated by thin polypropylene layers. The total thickness of the EMFi material is only a few dozens of micrometers.

The sensor operation is capacitive in nature and it is based on thickness variations in the midsection of the film caused by external force [7]. The change in thickness modifies macro dipoles and generates a corresponding charge and hence, a voltage to appear at electrodes. When the force is applied to the EMFi material, the thickness of the polymer layers will change much less than the thickness of the air voids due to their lower stiffness. Thus the electromechanical signal of the EMFi mainly arises from the movement of the charged polymer layers with respect to other layers and is not of piezoelectric origin.

II. Implementation

A. Sensor unit

The EMFi sensor being used is the L-series sensor which is a sheet sensor. It comes with a pre-connected connector which is heat-sealed on to the sensor. The sheet sensor is stuck to the chair with normal duct tapes. The chair used in this experiment has a flat seat surface for the sensor to be seated properly and has a backrest that will ensure the test subject is sitting comfortably and is relaxed because even slight movements can cause profound changes in the waveform as the sensor has very high sensitivity. As the chair is plastic it is resistance to most of the noises from the environment.

The EMFi sensor has a sensitivity of 25pC/N and the size of the sensor is 30cm x 30cm; the type of connector of the sensor is a ¼" male audio jack and known as a tip-ring-sleeve connector (TRS).

B. Amplifier Unit

As explained above to get the heart signal it is necessary to measure the displacement of charges, this can be done using a *charge amplifier*. Charge amplifier does not amplify the charge, in contrary it actually converts the small charge variations of the EMFi sensor to voltage variations by means of an operation amplifier circuit which has a capacitive feedback. The circuit is powered by two 9V batteries to supply the amplifier with positive and negative supply. To make the instrument simple and safe to use, this setup is implemented as a battery powered device. This also eliminates the noise coming from the power supply and through grounding [2].

The amplifier part has two stages; the charge amplifier and a voltage amplifier. Both these amplifiers are implemented using Texas Instruments TL082 which is low power, dual op-amp. It also has a high slew rate of 13 V/μs and supply current of 1.4mA. The second stage of the amplifier circuit is a voltage amplifier with a gain of 380. The RC time constant sets the frequency characteristics of the amplifier, and components are chosen with the frequency characteristics of the measured signal in mind. The value of the time constant used in this experiment was, T = R x C = 0.22s. To obtain this time constant the resistor was given a value of 10MΩ and the capacitance of 22nF was chosen. The circuit was soldered on to a PCB. Jumpers were used as connectors for assembly and disassembly of the circuit. The circuit was placed in an aluminum box along with the 9V batteries for the power supply. The input to the circuit is the charge from the EMFi sensor; the output of the two-stage amplification is the input for the Data Acquisition card (DAQ card). The DAQ card used is NI DAQ 6008. It has 11 bits as single ended inputs, a sampling rate of 10ksps and a bus speed of 1.2 Mbps. The DAQ card is connected directly to the laptop and operated through NI LabVIEW. The aluminum box is used to hold the circuit and the power supply. It has a hole to house the female connector for the audio jack. The main purpose of using the aluminum box is to shield the circuit from external electromagnetic disturbance. Aluminum creates an EMF when it is exposed to RF noise and if this EMF noise is grounded; it can easily be cancelled out. Hence, any circuitry present inside an aluminum box can be protected from RF waves. The box has been fabricated to house the battery supply which is separated from the circuit by a partition, and outlets have been provided for the 5mm female audio jack port and for the connection of amplifier circuit to the DAQ card.

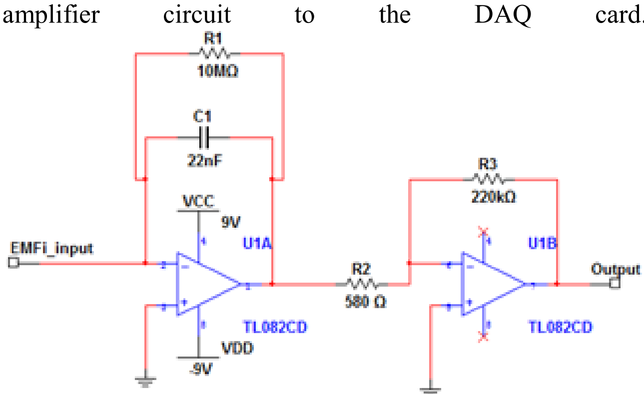

Fig. 3 Two-Stage Amplification

C. Software Unit

A software filter was implemented for the signals in order to get the BCG signal. Filtering in this case corresponds to removal of vibrations due to respiration, body movements and some other disturbances. It has been established that by using a highpass filter with cutoff frequency of 0.8Hz the presence of signal due to respiration can be minimized considerably. The program will also display the cardiac output by interpreting the waveform obtained.

For the purpose of ECG(used for validating the signal obtained from BCG), electrodes are connected in the Einthoven's triangle method. For obtaining the BCG signal, subject will be sitting on the EMFi sheet sensor. In this case the BCG signal obtained is due to the vibration caused when there is blood flow in the pulmonary artery. The EMFi sensor will be connected to the amplifier unit which is in turn connected to channel 0 of the DAQ card. The whole measurement electronics is kept in an aluminum box of 21.5 x 11.5 x 7 cm. The ECG electrodes are connected to the amplifier unit and in turn connected to channel 1 of the DAQ card. The DAQ card is connected to the laptop where signals are processed, monitored and compared using LabView

D. Calculation of Cardiac Output

Cardiac Output (CO) is calculated from the BCG signal. CO is termed as,

$$\text{CO} = \text{Stroke Volume (SV)} * \text{Heart Rate (HR)} \quad (1)$$

To determine stroke volume, analyse the BCG signal and obtain the maximum (MAP) and minimum peak values (MIP);

$$\text{MXG} = \text{MAP} \times \text{amplified voltage output} \quad (2)$$

$$\text{MIG} = \text{MIP} \times \text{amplified voltage output} \quad (3)$$

MXG is the maximum peak gain and MIG is the minimum peak gain. This will yield the number of charges displaced (NC)

$$\text{Force applied} = \text{NC} \div \text{Sensitivity of sensor} \quad (4)$$

So now there are two forces, one is from MAP and other is due to MIP for the first peak, say, FMAX and for the second peak, FMIN. It's been known that Pulse Pressure (PP) is the difference between systolic pressure and diastolic pressure. The FMAX and FMIN are forces due to systolic and diastolic activity. Now, from these forces it is possible to find the value of pressure from the well-known equation which relates force and pressure through area. In this experiment as the signal is obtained due to blood flow in the pulmonary artery area of pulmonary artery is taken into account to compute the systolic and diastolic pressures.

$$\text{PP} = (\text{FMAX} - \text{FMIN}) \div \text{Area of artery} \quad (5)$$

$$\text{SV} = \text{PP} \times \text{Constant} \quad (6)$$

This constant for our case was calculated by calibrating with Echocardiogram which can calculate the stroke volume; the echocardiogram of two subjects was taken and calibrated our BCG with the stroke volume obtained from the echocardiogram. On doing so, the constant was obtained to be around 3.33. Hence it can now be said that,

$$SV = PP \times 3.33 \tag{7}$$

To measure CO, the heart rate (HR) is determined from ECG as heart rate calculation from BCG signal is very complex. SO,

$$CO = SV \times HR \quad (L/min) \tag{8}$$

This is the cardiac output obtained from BCG on calibration with echocardiogram. Readings of 14 different volunteers was noted and it was observed that the cardiac output was in the range of 4 to 6 liters/min.

III. RESULTS AND CONCLUSION

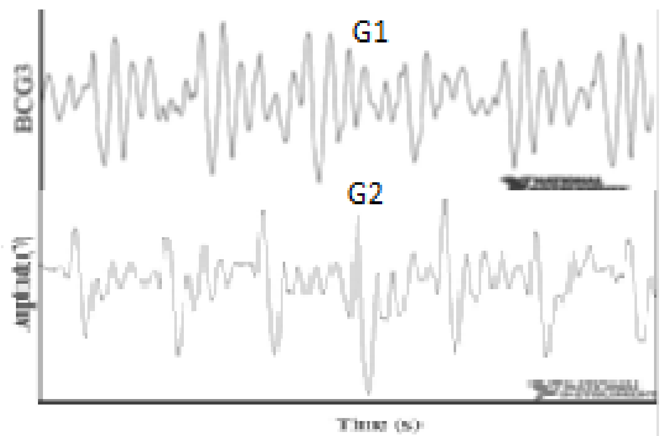

Fig. 4: Obtained BCG Graphs

Table 1 Cardiac Output Measurements(L/MIN)

SNO	DAY(L/min)	NOON(L/min)	NIGHT(L/min)
1	5.75	5.45	5.22
2	4.65	4.51	4.37
3	4.45	4.5	4.32
4	6.4	6.22	6.18
5	5.73	5.61	5.3
6	4.94	4.44	4.81
7	6.23	5.12	5.95
8	5.66	5.37	5.2
9	4.32	4.83	4.04
10	4.47	4.44	4.81
11	6.54	6.22	6.47
12	5.38	5.26	5.08
13	4.82	4.74	4.25
14	4.11	4.07	3.96

Readings were taken for 14 subjects (Table 1). On comparing readings, it has been found that people who have an athletic body give stronger heart vibrations when compared to others. For some hefty subjects, the BCG signal was a bit difficult to interpret. On analyzing the BCG signals were found to have overlapping signals which was a result of reverberations caused in the body due to respiration. Also the amplitude of the signal increased when the subject inhaled and reduced when the subject exhaled. G1 in the Fig 5 is the reading of the person taken in a standard room conditions. The graph G2 in Fig 5 was taken in the special facility AMBE (Amrita Bio-Medical Research laboratory) which has a complete noise free platform.

A setup was presented which could measure BCG in sitting position using a flexible, light-weight polypropylene film sensor EMFi on a normal looking chair. The properties of EMFi sensor have been mentioned, and its suitability to this application has been verified. A simple setup of ECG has been constructed for validation purposes. The readings of 14 healthy male subjects were recorded and a comparison between BCG and ECG was made. The BCG differed for every individual due to various factors like strength of heart beat, vibration conductivity of the body, amount of fat in the body, weight of the person etc. For cardiac output measurement, heart rate was determined from ECG and calculation of the same is difficult in BCG and complicated. BCG lagged ECG on an average of 0.1-0.3 s. This difference in time is called the PEP or pre-ejection period and is an important parameter for determining the health of heart.

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