A Novel Approach to Study Electrical, Mechanical and Hydraulic Activities of Heart and Their Coordination Based on ECG and PCG

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Abstract
Heart is a peculiar organ which performs its activity autonomously. Human body is a volume conductor of electricity having heart as a dipole inside it. Muscles of heart (myocardium) are richly supplied with the nerve fibers. The electrical, mechanical and hydraulic activities of the cardiac system are closely related to each other. Opening and closing of different heart-valves allow flow of blood from one chamber of the heart to the other and also to and from the whole body. In the simplest form, the sound produced due to flow of blood through various valves is heard by the physicians with the help of stethoscope while the electrical activity is recorded as ECG. These two are the most commonly adopted bases to primarily assess the heart condition. There exists a scope of looking at the heart activity from different perspectives. In this paper, the heart has been described as a combination of three major subsystems; the Electrical, the Mechanical and the Hydraulic subsystems. The results obtained through an experimental setup helped in identifying the synchronization of different subsystems in specified intervals. The simulated results in MATLAB environment and the results obtained through experimental set up established a perfectly coherent correlation among the three subsystems for a healthy person. This approach may open up a new dimension in modeling of activities of heart in engineering domain for better diagnostics.

Keywords: Electrical Subsystem, Mechanical Subsystem, Hydraulic Subsystem, ECG (Electrocardiograph), PCG (Phonocardiograph), GUI (Graphical User Interface), Valves, Myocardium.

Introduction
Nowadays, a lot of development is there in the field of the biomedical engineering. Whether it is a latest technique or a new system, they all aim at enhancing the reliability and accuracy of the data leading to the most specific diagnosis. In the field of biomedical sciences the cardiology has been one of the most trending arenas in which the maximum research and developments are going on. Heart is the supreme organ of the body. Incidentally majority of the population suffers from its ailments. Malfunctioning of heart includes many disorders like cardiomyopathy, prolapsing of arterial valve, arrhythmias, coronary artery problem and vascular disease etc.

The accurate detection of a cardiac defect is the prime concern for its proper diagnostics and treatment. The basic and the most popular method adopted for the investigation of the cardiac activity is through electrocardiography (ECG). It records only the electrical activities of the heart. The heart performs multiple coordinated activities including electrical, mechanical and hydraulic ones. These activities occur in a cyclic manner with time period of a fraction of a second. These activities are inherently interdependent and are correlated with each other.

Figure 1 depicts that in one cycle of heart beat, the three activities comprising of ECG, PCG and the volume-pressure relationship are performed simultaneously. First one is the electrical activity that is the generation of electrical impulses at the Sino Atrial (SA) node which marks the beginning of the activity cycle. The generated signal passes through Atrio Ventricular (AV) node, bundle of his and then to the Purkinje fibers [1-2]. These electrical impulses, while travelling through various parts of the heart, result in the mechanical activity which includes the contraction and relaxation of the heart muscles.

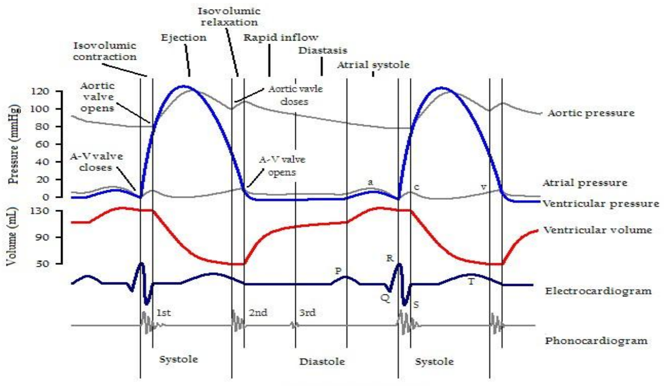

Figure 1: Electrical System of Heart [1]

The contraction leads to the opening of different valves whereas the relaxation leads to the closing of the valves. Due to the different actions of cardiac muscles, and the opening and closing of the valves; the blood flows in and out of the heart chambers. The mechanical activity is analyzed with the PCG signal [3]. Third activity is the hydraulic activity which is also one of the prime activities that includes the stroke volume and corresponding pressure of the blood flowing through different chambers of heart. During systolic period, the blood flows inside the heart chambers. While during diastolic period it flows outside the heart chambers in order to get distributed via a number of veins and arteries throughout the body. The opening and closing of the valves solely depend on the pressure generated and the volume of the blood inside the four chambers [4].

The heart defects occur mainly due to improper functioning of any one or more of the above three activities. It is important to identify the defects to make an accurate diagnosis for treatment. An exclusive study of the performances of each of these three activities or subsystems separately may improve upon the existing diagnostic techniques.

Subsystems Of Heart

Electrical Subsystem of Heart

Most systems of human body generate bioelectric potentials that have their own characteristic of de-polarization and re-polarization using suitable transducers (body electrodes) and other associated biological circuitries. These natural bioelectric potentials get converted into corresponding electrical signals and are measured and recorded for diagnostics. The heart can be viewed as a source of electricity, surrounded by electrically conducting media. The SA node is an independent natural source of electrical signal which is also known as natural pacemaker. The electrical impulses get generated at the SA node in regular intervals and get conducted over the various parts of the heart. The impulses normally travel from SA node through the AV node (at atrium), bundle of His, Purkinje fibers to reach the ventricles.

The time between two consecutive beats of heart constitutes one cycle. The algebraic sum of the action potentials of myocardial fibers is recorded from the surface of the body. The pattern of ECG depends on individual physiological condition, age, posture and also on placement of electrodes. On comparing the nature, frequency and magnitude of this ECG record with the test record, conclusions are inferred and the diagnosis is made. Figure (2) shows the block diagram of electrical activity, that is the flow of electrical signals in the heart.

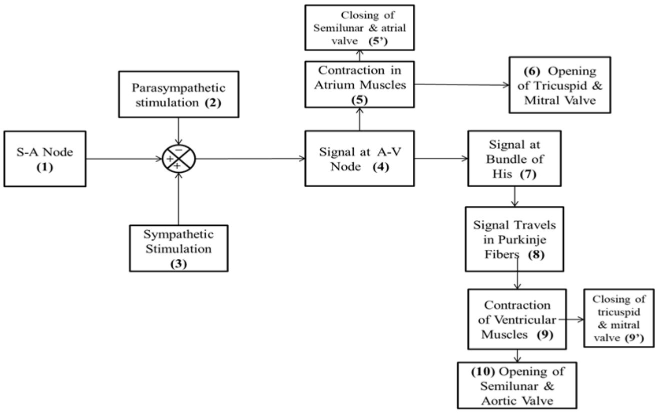

Figure 2: Block diagram of Electrical Subsystem

The SA node is an autonomous natural electrical signal generator. The signal from SA node gets superimposed by the Sympathetic and Parasympathetic stimuli that increase and decrease the heart rate respectively [5-6]. The resultant signal goes to the AV node due to which the muscles of Atrium get contracted. As a result of this, the Tricuspid and the Mitral valves get opened allowing the flow of blood from right and left atria to the right and left ventricle chambers respectively. The electrical signals further travels through Bundle of His to the Purkinjee fibre. In this duration it contracts the ventricular muscles. The Tricuspid and Mitral valves get closed in this duration due to increased pressure inside the ventricle chambers caused by its contraction. This also leads to opening of the Aortic and Semilunar valves [7]. The blood rushes from right and left ventricle chambers through the Aortic and Semilunar valves to the Aorta and the Pulmonary Arteries respectively. The pressure of blood in this duration is known as 'Systolic' pressure and this is more than the diastolic pressure. The vector representation of the electrical signal with respect to time is known as the ECG record. The signal is obtained by placing the electrodes at different locations of the heart as well as at both the upper and the lower limbs, taking right leg as reference. One cycle of ECG represents the vector potential analysis of one electrical cycle of the heart.

The force of contraction depends upon the initial length of fiber, duration of previous diastolic pause, nutrition and oxygen supply [8]. During contraction, also known as refractory period (equals 0.2 sec for heart rate up-to 100 beats per minute), the myocardium does not respond to external stimulus.

Mechanical Subsystem of Heart

The energy is provided by the electrical subsystem to the mechanical subsystem to facilitate the functioning of heart [6]. Mechanical subsystem mainly deals with opening and closing of the heart valves. All the four valves are normally closed type valves. In other words they remain closed as long as no external activation is provided to them. Primarily they get opened due to contraction (caused by electrical activation) and pressure difference (caused by filling up of the chambers) which are resulted by the electrical conduction in the heart muscles and flow of blood respectively. As soon as any valve gets opened, the blood starts filling in or out the ventricular chambers. There are tissues (Chordae tendinae) attached between the valves and the papillary muscles connected with muscular walls of the ventricular chambers [9-11]. These tissues get stretched due to increased pressure inside the ventricular chambers.

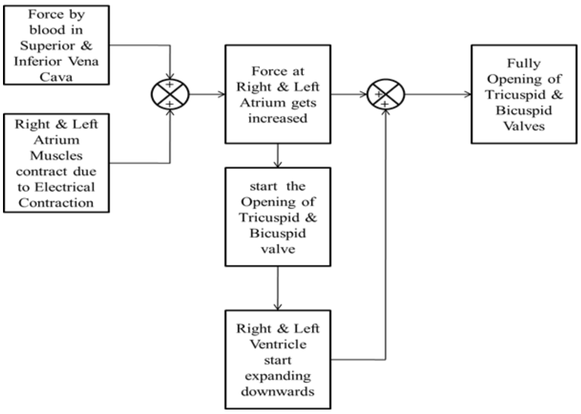

Figure 3a: Mechanical Subsystem (opening T and M Valve)

The block diagram given in Figure (3a & 3b) explains the activities of the mechanical subsystem of the heart. In the discussion here it is assumed that the Tricuspid and the Bicuspid valves; and the Aortic and the Semilunar valves; function simultaneously. Let us first discuss the activity at Atrium as shown by the block diagram in Figure (3a). The closed position of the tricuspid valve prevents the impure blood to flow from the right atrium to the right ventricle.

The deoxygenated blood brought to the right atrium by the superior and inferior vena cava from the upper and the lower parts of the body respectively, exerts pressure on the Tricuspid valve. The pure blood, brought to left atrium from the lungs by pulmonary veins, exerts pressure on Bicuspid valve. At the same time the electrical signal travelling from SA node to the AV node leads to contraction of the atria. As a result of the two, the valves start opening. Elongation of the ventricular chamber and filling up of blood in it, leads to further opening of the valves. So, the cumulative effect of expansion of valves and the presence of blood under pressure in the atria, leads to fully opening of the (Tricuspid and Bicuspid) valves and the filling of blood in the ventricle as shown in the block diagram.

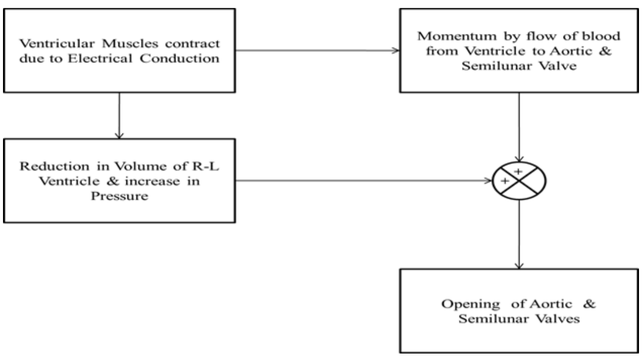

Figure 3b: Mechanical Subsystem (opening A & S Valve)

In ventricle, the flow of impure blood from right ventricle to the lungs through pulmonary artery is controlled by the Semilunar valve. Similarly the flow of pure blood from left ventricle to the whole body through aorta is controlled by the Aortic valve. As shown in the block diagram of Figure (3b), the electrical conduction in ventricular muscles leading to its contraction has twofold results. It gives momentum to the blood stored in the ventricles as well as reduces the volume of blood inside them causing an increase in the pressure [12]. As a result of the two, the Semilunar and Aortic valves get opened.

Hydraulic Subsystem of Heart

Basically the heart functions like a powerful pump. It receives the deoxygenated blood from the body and pumps it to the lungs for purification. Also it receives the oxygenated blood from the lungs and pumps it back to flow in the whole body. Energy exchange takes place from electrical to mechanical and hence to hydraulic subsystems of the heart as described in the block diagram shown in Figure (4).

Contraction of Atria leads to development of force on the Tricuspid and Bicuspid valves. This diastolic activity leads to opening of these valves to allow flow of blood from Atria (L & R) to Ventricles (L & R) thereby releasing pressure. After the expiry of approximately 60% of the heart cycle, i.e. after the contraction period of ventricles and pushing off the blood to ventricles are over; a momentum gets created inside the ventricular chambers.

This leads to closing of Tricuspid and Bicuspid valves. The momentum of ventricles along with the pressure differences (between the right ventricle and the pulmonary artery; and the left ventricle and the aorta) lead to opening of the Semilunar and Aortic valves. In this systolic period of the heart activity, the heart pushes the blood outside [13-14]. The pure blood is pushed to the body and the impure blood is pushed to the lungs.

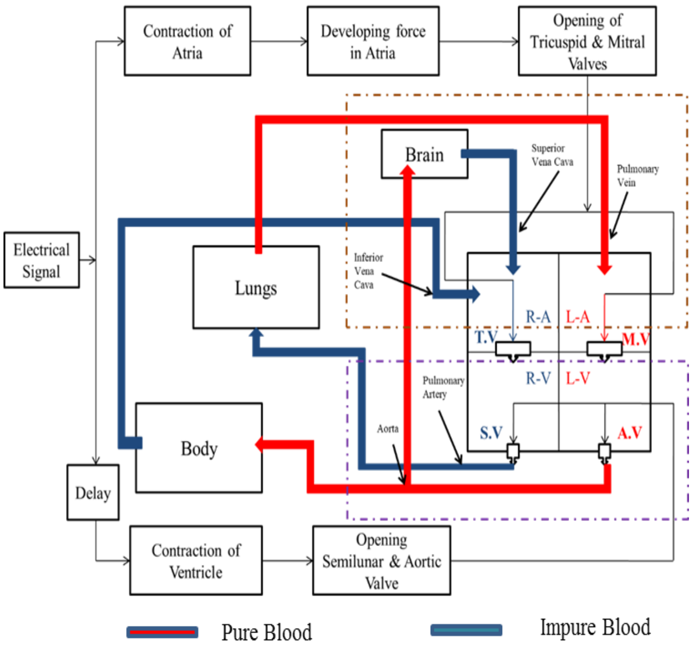

Figure 4: Hydraulic Subsystem of Heart

Sounds of Heart

The heart sounds are normally produced due to the closure of valves of the heart. During shutting of the valves, the cusps of valves and the chamber walls vibrate creating sounds. The two major sounds produced are designated as S1 (Lub) and S2 (Dub). Lub is louder than the Dub sound. S1 and S2 are related to closure of Atrioventricular valves and Semilunar valves respectively. Whereas the S1 comes at the beginning of the ventricular systole, S2 comes towards its end and at the beginning of diastole.

Experimental Setup

Experimental setup was developed to obtain the heart's electrical signals using CARDIART 108T/MK, BPL ECG machine. This machine gives analog electrical data. Similarly the sound signals were obtained through a stethoscope, giving real time signals of heart sound. An indigenous approach was adopted to fetch electrical signal of heart sound. A general purpose microphone was fitted inside the pipe of the conventional stethoscope to get the electrical signals from it. An electrical circuit using interfacing card and differential op-amp was developed to transfer these real time continuous signals to a PC. The signals were then processed and interfaced in real time frame in the Graphical User Interface (GUI) platform of MATLAB software. The model developed in MATLAB used analog data input, analog filter and scope etc.

Results and Discussion

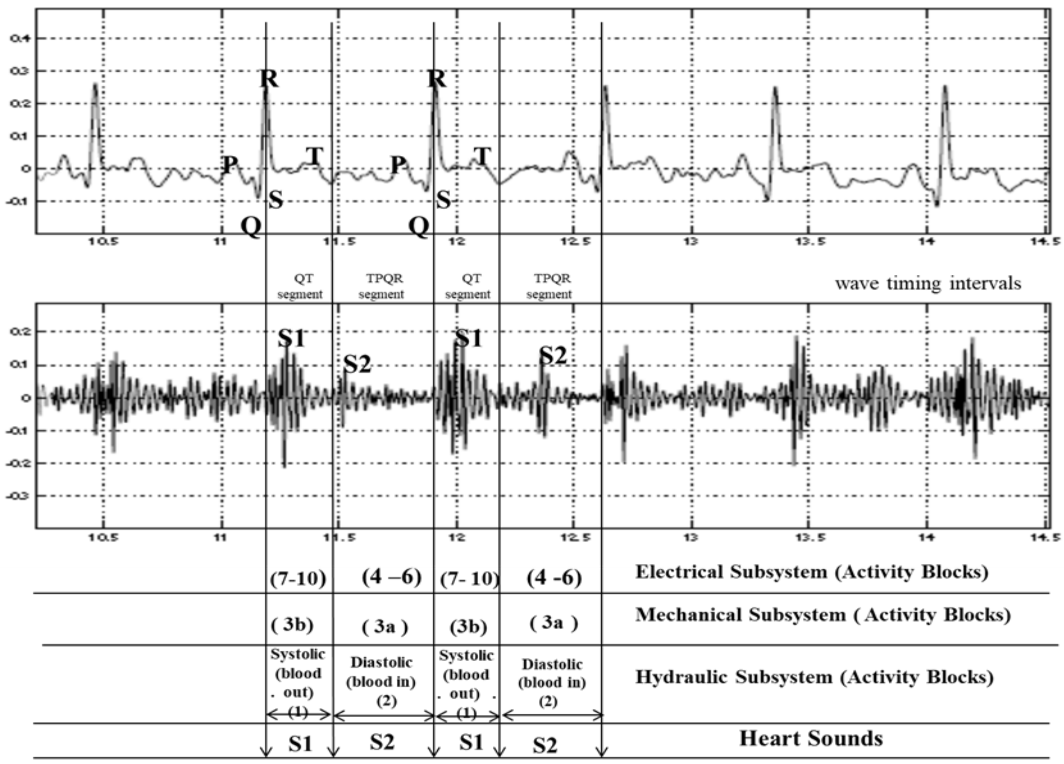

Figure 5: Correlation of Electrical Mechanical & Hydraulic Subsystem of Heart

The ECG and PCG signals of a healthy person were captured in real time and were plotted together. A sample for duration from 10th to 15th second has been shown in Figure (5). The R-R interval shows one cycle of the heart activity. The electrical signal RST is responsible for initiating and controlling the mechanical and the hydraulic activities that produce the first heart sound (S1).

S1 appears at the commencement of systole and is heard over the QT segment of ECG signal. Similarly the TPQR signal is responsible for production of the second heart sound S2 during Commencement of diastole and is heard after the QT segment in the ECG as depicted in Figure (5).

The electrical, mechanical and hydraulic activities of the heart are interdependent and are synchronized with electrical activity. All these activities of subsystems are depicted in Figures (2, 3 and 4) in which each block is numbered. The actions performed by each of the subsystems during various intervals in one cycle of heart are described in Figure (5) through their functional block numbers to bring about the interdependence and synchronism among different subsystems for understanding of the holistic activity of heart.

Conclusion

The paper highlights the fact that the functioning of heart is a complex combination of the activities of its electrical, mechanical and hydraulic sub systems. The self-initiation of electrical signal and its transmission to various parts of the heart results in mechanical activity in terms of contraction of its muscles. This leads to development of pressure differences between various chambers of the heart causing the opening and closing of various valves to facilitate blood circulation. The heart's electrical activity is recorded by ECG whereas its mechanical and hydraulic activities together manifest in terms of sound signals that are recorded as PCG signals. It has been established that there exists interdependence among the electrical activity, mechanical operation of valves and the hydraulic flow of blood through the valves resulting in development of heart sound.

They all bear a definite coordinated relationship over a complete cycle of one heartbeat. The real time data acquired from the experimental setup significantly demonstrated that the actions of the various subsystems of a healthy heart occur in perfect synchronism as the ECG and PCG signals exhibit perfect synchronism. At the same time, the results are indicative of the fact that this synchronism may tend to differ if the condition of heart tends to shift from normalcy.

An attempt has been made in this paper to judiciously segregate the electrical, mechanical and hydraulic activities of hart and model them as independent subsystems. The intention is to develop an understanding of the roles of each subsystem in normal functioning of heart. This may open up a fresh dimension to unleash their roles and to unravel their individual contribution towards normal and abnormal functioning of heart.

The presented modeling and interpretation may contribute towards better understanding of the performance of heart. This dissected approach of study of heart activity may develop deeper physical insight into the subject matter in order to reason out the abnormalities and relate it to the extent of contribution of each subsystem. This may add a new dimension in diagnostics of cardiac diseases.

Acknowledgement

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