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Introduction

1.1 MOTIVATION FOR HEART MONITORING

The main objective of this thesis is to reduce the morbidity and mortality rate due to cardiovascular diseases (CVDs). CVDs are serious health problems all over the world. Following are few facts related to CVDs indicating its seriousness that motivated us to work in this area.

1.1.1 Burden of CVDs Worldwide

Worldwide, CVDs have been and continue to be the single largest cause of death [Finegold et al., 2013]. Mortality caused by CVDs in 2008 was 17.3 million, which represents 30% of global deaths, shown in Figure 1.1. In 2014, CVDs are reported to be responsible for 42% of all deaths in European Union [Nichols et al., 2014]. In recent years, tremendous advancements in cardiac care including drugs, implant devices, and diagnostic innovation, reduced the mortality rate of people belonging to developed countries [Commission, 2014]. On the other side, in low-and-middle income countries, such deaths account for more than 80% of global deaths due to CVDs [Finegold et al., 2013].

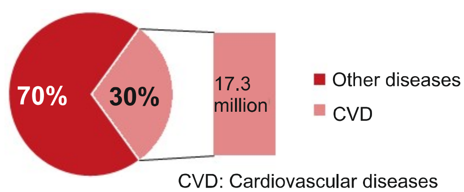

Figure 1.1 : Mortality due to CVDs, Worldwide

The number of people who make heart-diseases-related visits to their physicians is about 12.4 million, worldwide, every year [Healthline, 2014]. On average, these people stay in the hospitals for about 4.6 days. This large number of visits to the hospital and staying in the hospital causes the economic loss as well as the productivity loss of the patients and their relatives.

According to American Heart Association (AHA) report, the total cost of CVDs and stroke in the U.S. in the year 2009 is estimated to be $312.6 billion [Organization, 2010], while in Europe, overall cost due to CVDs is estimated to be almost $219 billion a year [Nichols et al., 2014]. In this estimated cost, around 54% is due to health care cost, 24% due to productivity losses and 22% due to the informal care of people with CVDs.

1.1.2 Burden of CVDs in Indian Context

CVDs have been leading cause of morbidity and mortality in India as well and this burden is increasing every year [Deloitte, 2011]. It is reported that the CVDs were the fastest growing chronic illnesses between 2005 and 2015, growing at 9.2% annually. The number of patients suffering from CVDs is 45 million in 2008, which is approximately equal to the summation of the population of India's two states Haryana and Punjab, while, 2.4 million die every year due to CVDs [Deloitte, 2011].

In India, the burden of CVDs is huge due to the inadequacy of the health services and related experts. According to a report [Deloitte, 2011], 70% of the population of India live in rural areas where only 13% have access to primary health care. Although this number is improving, still the availability of the medical professionals is very low. According to the WHO, there should be one doctor on one thousand people, while in India there is one doctor for 1700 people. Furthermore, India trains only about 150 cardiologists every year [Deloitte, 2011] and hence the number of patients to doctor ratio, in such cases, is prohibitively high.

Same as in case of other similar countries, Economic loss due to CVDs is also huge in India. According to a study, from 2005 to 2015, approximately ₹ 130 trillion was the expenditure towards the treatment of the CVDs. Due to the expensive treatment and financial constraints, approximately 28% of CVDs go untreated.

1.2 OBJECTIVES OF THE THESIS

The above-mentioned facts indicate the seriousness of the CVDs and the requirement of research focus in this field. The major problem with the CVDs is that their symptoms occur, sometimes, at a later stage when the situation get worse. Lack of early-stage detection and hence delay in medication causes heart diseases to extend to a level where it is difficult to cure [for Disease Control and Prevention, 2002]. Therefore, it is of paramount importance to diagnose the CVDs at an early stage by which timely medication can be initiated and hence the impact of CVDs can be reduced considerably. A long-term monitoring is expected to provide an early diagnostic marker of the heart diseases because these markers, which may appear random, will leave their signature if the patient undergoes for long-term monitoring [Yamakawa et al., 2013; Medtronic, 2012; Hu et al., 2014; Koivisto et al., 2015]. Thus, with long-term monitoring, such diseases can be diagnosed at an early stage [Jiang and Choi, 2006].

Continuous monitoring is also needed in cases of persons diagnosed with CVD, as they are at a higher risk to their lives as compared to the normal persons. According to the Heart Association, people diagnosed with CVD have 4 to 6 times higher mortality risk than normal ones [Choi et al., 2005].

In view of the burden of CVDs and the benefits with long-term monitoring, as discussed above, the objective of this thesis is to improve the existing system in terms of following features.

- Portability
- Convenient to wear
- Robust to noises
- Easy to operate
- Automatic screening capability
- Cost effective

A system with these features is favourable for home monitoring and remote monitoring. Enabling a system to be used at home and the availability of requisite information at a remote location will reduce the requirement of frequent hospital visits and will also reduce the mortality rate [Jiang and Choi, 2006]. Such features will also be supportive for elderly patients staying alone at home. Ease of operation and portability features of the system will be useful in rural areas where such health care facility is still in its infancy and inadequacy of health experts [Deloitte, 2011]. A cost-effective system will be favourable for its use in low and middle-income countries. Proper diagnosis reduces the mortality caused due to CVD, which ensues economic uplift of the country [WHO, 2011].

To address these requirements, a lot of work has been done towards the development of a diagnostic efficient cardiography system. Cardiography systems diagnose the health status of the heart using the heart signal produced during each cardiac cycle. Many types of sensors have been used to acquire heart signals in different forms such as electrical signal, acoustic signal, seismic signal and optical signal. Based on the underlying sensor, cardiography systems have been named as electrocardiography, phonocardiography, seismocardiography, and photoplethysmography.

1.3 CARDIAC ANATOMY AND CARDIAC CYCLE

Since understanding of these cardiography systems needs knowledge of the physiology of the heart and its functioning, cardiac anatomy and cardiac cycle are described in the following section.

1.3.1 Cardiac Anatomy

The heart is a prominent organ of the human body. It supplies replenish oxygen to each part of the body and removes the waste of each cell. Physiologically, the heart is comprised of four chambers named as left and right ventricles, and left and right atrium, as shown in Figure 1.2. There are two atrioventricular valves namely tricuspid valve and mitral valve. As can be seen in Figure 1.2, tricuspid valve separates the right atrium and right ventricle while mitral valve separates left atrium and left ventricle. Aortic valve and pulmonary valve jointly called semilunar valves, separate left and right ventricles from the aorta and pulmonary artery respectively. The wall separating the left and right atrium is called as atrium septum and the wall separating the left and right ventricles is called as ventricle septum.

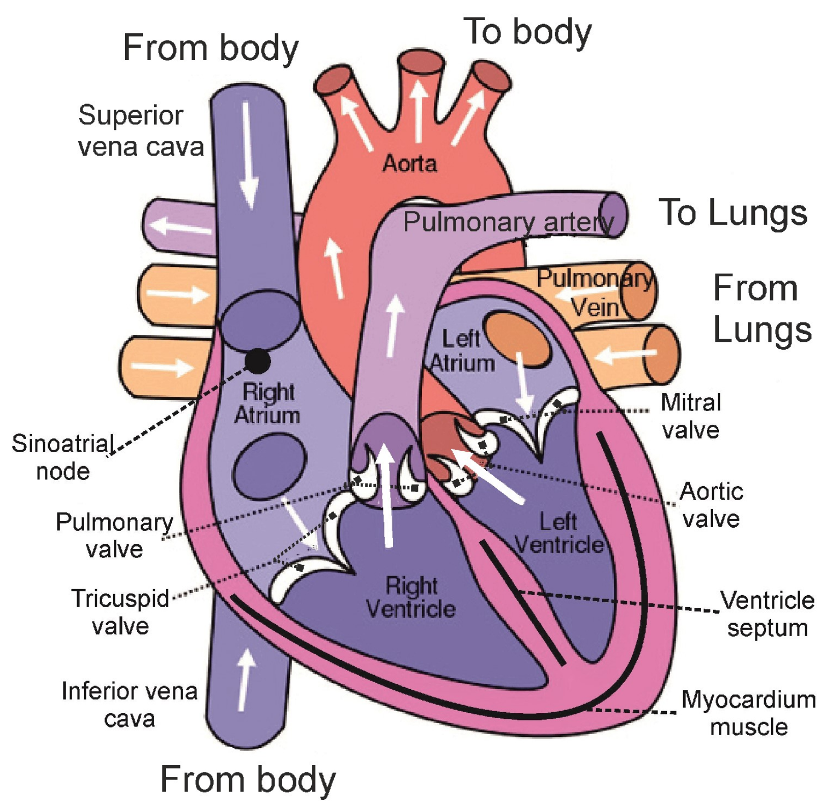

Figure 1.2 : Anatomy of the human heart

1.3.2 Cardiac Cycle

At rest, each cell of the heart muscle has a negative charge, called the membrane potential. Due to rapid change of membrane potential towards zero, due to influx of positive cations (Na+ and Ca++), an electrical impulse is generated at sinoatrial node, as shown in Figure 1.2. From sinoatrial node, the impulse spreads over both the atrium and both the ventricles. The presence of the impulse causes the contraction of atria and ventricles sequentially. Contraction of both atria pushes the blood into respective ventricles. Then the impulse spreads all over left and right ventricles causing the contraction of both the ventricles. This contraction results in the closing of both atrioventricular valves and opening of both semilunar valves. During this contraction phase, oxygenated blood from the left ventricle flows into the body through the aorta while deoxygenated blood, from the right ventricle, flows into the lungs through the pulmonary artery for oxygenation. Since body and lungs receive blood due to contraction process, pressure in the body and lungs becomes higher than the pressure in the atrium. Due to this pressure difference, now, blood flows into left and right atrium from the lungs and body respectively. This process completes a cardiac cycle.

1.4 POPULAR CARDIOGRAPHY SYSTEMS

Heart function may be affected due to many factors such as psychosocial stress, smoking, excessive use of alcohol, malnutrition, lack of physical activity, and congenital diseases [Curtis and Jr, 2002]. These factors may affect the electrical activity of the heart, the structure of the heart, and vascular system. Due to these defects, different heart diseases occur. Dysfunction of the electrical conduction system causes diseases such as sinus arrhythmia, atrial fluttering, atrial fibrillation, ventricular fibrillation, atrioventricular block and bundle branch block. Defects in the structure of the heart cause regurgitation, stenosis, enlargement of the chambers and ventricular septum defect. Defects in vascular system cause hypertension, stroke, Myocardial Infarction (MI) etc. Therefore, various types of sensors have been used to diagnose different type of abnormalities. Based on the underlying sensor used, cardiography systems have different nomenclature.

1.4.1 In Clinical Use

Popular cardiography systems used in the clinics are described in following subsections.

(a) Echocardiography

Echocardiography is the most commonly used imaging method based on ultrasound technique. In this technique, short pulses of high-frequency sound are transmitted through the heart and then the reflected sound waves or echoes provides the information about cardiac dimension, as shown in Figure 1.3. Inge Edler and Hellmuth Hertz, in 1954, reported the first echocardiography recording system [Edler and Hertz, 2004]. At present, cardiac imaging modalities play a crucial role to improve the diagnostic capabilities and the clinical management of patients with different cardiac diseases, including heart failure, valvular heart disease, myocardial infarction and atrial fibrillation. However, their performance accuracy significantly depends on the acquisition of the image for which experts are needed. Moreover, large and costly equipment and requirement of trained staff limit its widespread use.

(b) Electrocardiography (ECG)

Initial ECG was based on string galvanometer and was invented by Willem Einthoven in 1903. As discussed previously, an electrical impulse originates at sinoatrial node and then travels through the atria and the ventricles. ECG measures the electrical activity of the heart using electrodes placed on both sides of the heart. The measured signal consists of different waves named as P, Q, R, S, T and U [Goldberger, 2006], as shown in Figure 1.4. P wave rep-

Figure 1.3 : Echocardiography

resents atria contraction, while Q, R and S waves (called as QRS complex) reflect contraction of both left and right ventricles. T wave represents relaxation of the ventricles and U wave is caused by the relaxation of the inter-ventricular septum. Thus, duration and amplitude of these waves provide significant information for diagnosis of health status of the heart. However, amplitude of some of the waves (P, T and U) is very weak, typically in the range of 100 μV to 300 μV and due to this, the extraction of the duration of these waves is difficult [Webster, 1995]. Major problem with ECG is to establish good electrical conductivity between the skin and the electrodes.

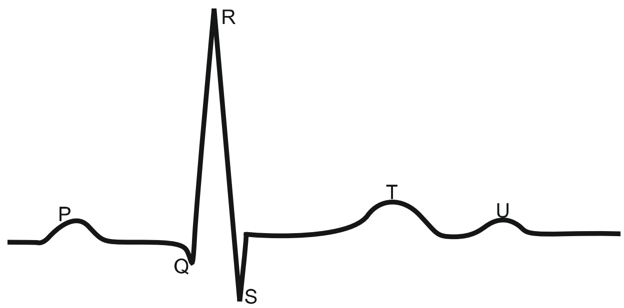

Figure 1.4 : Single cardiac cycle represented by ECG

(c) Phonocardiography (PCG)

PCG is most widely used method in clinic as screening tool for diagnosis of CVDs because of its features including easy to operate and timeless set-up process [Leng et al., 2015; Chourasia et al., 2014; Messer et al., 2001]. It uses a sensor called stethoscope. Stethoscope makes PCG a highly portable, low cost, and non-invasive cardiography technique [Boutana et al., 2011]. PCG signal, as shown in Figure 1.5, consists of two Fundamental Heart Sounds (FHS) known as S1 (Lub) and S2 (Dub). As discussed previously, the presence of the electrical impulse at ventricles causes both the ventricles to simultaneously contract that closes the atrioventricular valves. This prevents backflow of blood into the atria. Closing of the atrioventricular valves generates the first heart sound S1. The ventricular pressures will later drop below the pressures of the pulmonary artery and the aorta (end of the systole). It causes closing of the semilunar valves to prevent backflow of blood into the ventricles. The closing of these valves produces the second heart sound S2.

S1 is the loudest sound component in the heart sound signal composed of energy in 20-120 Hz frequency band and 110-150 ms in time duration [Boutana et al., 2011]. S1 is composed of two components: one due to the closing of the mitral valve, while another one is due to the closure of the tricuspid valve. Mitral sound component precedes tricuspid sound component as the left ventricle contracts slightly (typically 10 ms) before the right ventricle [Reed et al., 2004; Debbal and Bereksi-Reguig, 2008a]. S2 is generated due to the closing of aortic and pulmonary valves [Boutana et al., 2011]. As S1, S2 is also composed of two components: the aortic (A2) and pulmonic (P2) components with A2 occurring, typically 30 ms, before P2 [Reed et al., 2004]. The period between S1 and S2 is called as systole, while the period between S2 and next S1 is called as diastole.

There are two more components other than FHS in heart sound signal, S3 and S4, and they rarely occur. The S3 sound occurs due to the rapid filling of the ventricles and appears at the beginning of the diastole, immediately following the opening of the atrioventricular valves. This sound occurs between 100-200 ms after the aortic valve closure. The frequency of this sound is generally in the range of 70-90 Hz. The S4 sound occurs in late diastole, just after atria contraction, and it may be due to ventricular hypertrophy or pulmonary arterial hypertension [Beritelli and Serrano, 2007]. Murmurs are additional sounds lie within the frequency band of 100-700 Hz [Boutana et al., 2011]. They indicate diseases in the heart such as aortic stenosis, pulmonary stenosis, mitral regurgitation, and mitral stenosis.

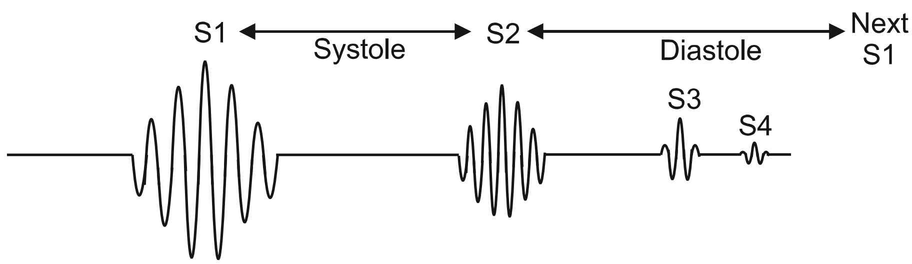

Figure 1.5 : Single cardiac cycle represented by PCG

(c) Photoplethysmography (PPG)

In the PPG, fluorescent body part such as earlobe and finger is illuminated with lights of different wavelengths emitted from Light Emitting Diodes (LEDs). Then the intensity of transmitted or reflected light is measured by photo-diode [Krishnan et al., 2010]. The measured intensity varies in time with the heart beat because blood vessels expand and contract with each heartbeat.

A typical PPG waveform, also known as Digital Volume Pulse (DVP), consists of systolic and diastolic waves, as shown in Figure 1.6. The systolic wave is a result of the direct pressure wave travelling from the left ventricle to the periphery of the body and the diastolic wave is a result of reflections of the pressure wave by the arteries of the lower body [Elgendi, 2012]. Reflection Index (RI) and Stiffness Index (SI) can be determined from the relative heights and the timing of the diastolic wave and the systolic wave as shown in Figure 1.6. Major challenge with the PPG is the vulnerability of its signal to motion artefacts and ambient light sources [Krishnan et al., 2010; Awodeyi et al., 2013].

1.4.2 Other Systems

The above discussed cardiography systems are widely used in clinic for the diagnosis of health status of the heart. In addition to these cardiography systems, researchers have made numerous attempts to improve diagnostic efficiency of cardiography system and to improve features for long-term use of it. For this purpose, various other cardiography systems have been explored for the monitoring of the health of the heart for the long-term. Following are three such cardiography systems.

(a) Impedance Cardiography (ICG)

ICG is a non-invasive technique that measures changes in the thoracic electric impedance (Z), caused by variation in blood volume during the cardiac cycle. [Pandey and Pandey, 2007; Yanqun et al., 2001]. The time derivative of the thoracic impedance $\left(-dZ/dt\right)$ is known as ICG. A typical ICG signal of a cardiac cycle is shown in Figure 1.7 [Ulbrich et al., 2014]. Point ‘A’

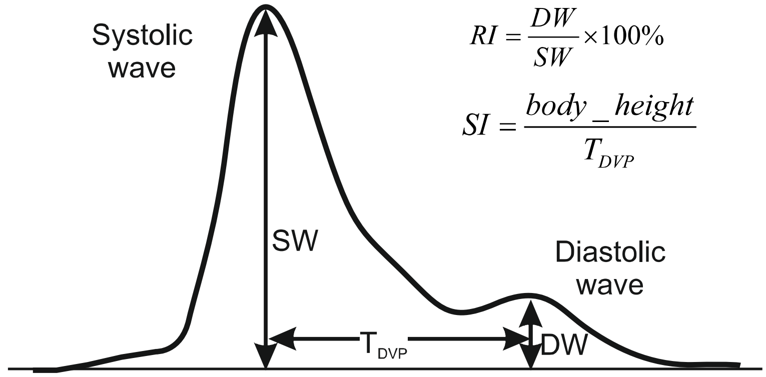

Figure 1.6 : Single cardiac cycle represented by PPG

represents the start of the electromechanical systole, point 'B' represents the opening of the aortic valve, point 'C' represents maximal mechanical contraction, point 'X' represents the closure of the aortic valve and point 'O' represents the opening of the mitral valve [Ulbrich et al., 2014]. ICG has been used as a promising technique to measure hemodynamic parameters such as Stroke Volume (SV) and Cardiac Output (CO), both of which reflect the health status of the heart.

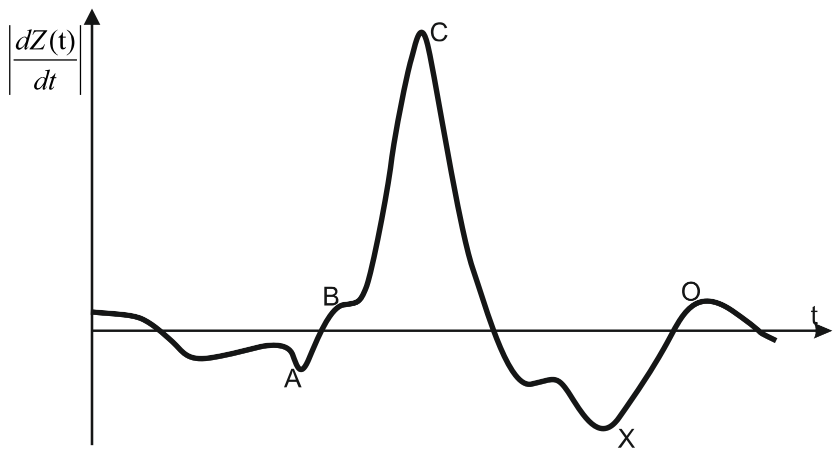

Figure 1.7 : Single cardiac cycle represented by ICG

(b) Seismocardiography (SCG)

SCG is another non-invasive technique which uses an accelerometer to measure precordial vibrations generated by heart movement [Zanetti and Salerno, 1991; Jerosch-Herold et al.]. SCG is convenient to patients, as there is no need for multiple electrode contacts as in the ECG. Furthermore, small size and low weight of Micro-Electro Mechanical System (MEMS) accelerometer makes it convenient to wear.

As shown in Figure 1.8, various cardiac events can be extracted from the SCG signal including Mitral valve Closure (MC), Isovolumic Movement (IM), Aortic Opening (AO), Rapid systole Ejection (RE), Aortic valve Closure (AC), and Mitral valve Opening (MO) [Salerno et al., 1991; Wilson et al., 1993; Tavakolian et al., 2014]. Using these cardiac cycle events, several diagnostically important cardiac cycle periods have been obtained, such as Left Ventricular Ejection Time (LVET) [Tavakolian et al., 2014], Pre-Ejection Period (PEP) [Tavakolian et al., 2014], systole and diastole [Tavakolian et al., 2013], and quiescent phase [Wick et al., 2012, 2015]. It has shown high reliability and accuracy to diagnose CVDs [Salerno et al., 1991] and to extract cardiac periods [Tavakolian et al., 2013; Wick et al., 2012, 2015].

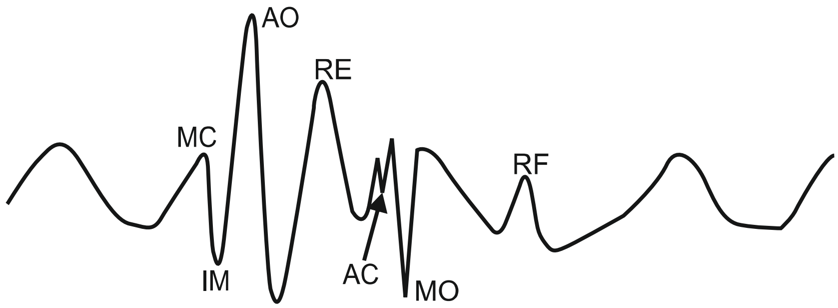

Figure 1.8 : Single cardiac cycle represented by SCG

(c) Ballistocardiography (BCG)

BCG refers to the measurement of the human body displacement caused by the heart beat and blood ejection [Scarborough et al., 1956]. Compared with other systems, the main advantage of BCG is that it can provide an unobtrusive way to monitor the heart condition, since, sensors do not need to be in direct contact with the human body.

BCG and SCG both methods are used to study the mechanical vibrations, which are produced by cardiovascular activities. BCG is a method where the cardiac reaction forces acting on the whole body are measured. SCG, on the other hand, is a method where the local vibrations of the precordium are measured [Chuo et al., 2009].

1.5 IMPORTANCE OF HEART SOUND BASED DIAGNOSIS

As discussed in the previous section, various cardiography systems have been evolved to address issues in heart monitoring. Due to different origination, each method presents a separate set of issues and challenges [Messer et al., 2001].

Heart sounds are produced due to the motion of the heart and vibration of the vascular structure of the heart. These sounds can be acquired from the surface of the chest. Thus, heart sound signal based cardiography systems are non-invasive in nature, portable, and affordable for repetitive use. Analysis of heart sound signal provides crucial diagnostic information about various cardiovascular pathologies [Kwak and Kwon, 2012; Choi and Jiang, 2008; Elgendi et al., 2014]. It is because, mechanical activity of the heart is governed by various physiological parameters including blood pressure, tension in the heart or in adjacent vessels, ventricular volume, blood flow velocity, and deformation of the heart wall [Vermarien, 2006]. Thus, any abnormality in these parameters will be reflected in the mechanical activity of the heart and consequentially in the heart sound signal. Therefore, the heart sound signal has been thoroughly explored for health monitoring and medical diagnosis [Fatemian, 2009].

In addition to it, the heart sound signal has been used extensively for diagnosis of valvular heart diseases [Boutana et al., 2011]. Valvular heart disease is one of CVDs diseases which is increasing every year [Vuyisile et al., 2006]. In the U.S. alone, more than five million are diagnosed with heart valve diseases. Within this group, approximately, two million people suffer from mitral regurgitation, while, half a million people are affected by aortic stenosis [Enriquez-Sarano et al., 2009]. In case of both the diseases, studies show that approximately 50% of patients were not referred to further evaluation and intervention due to the absence of symptoms [Enriquez-Sarano et al., 2009; Bach, 2011; Jiaquan et al., 2010]. This means that in 50% cases the valvular diseases were not timely diagnosed. It is also reported that without timely intervention and proper medication, patients are less likely to survive for more than 2.6 years [Markwick et al., 2012; Otto, 2000]. These numbers indicate the seriousness of the heart valvular diseases and indicate need of an affordable and portable system to diagnose them at an early stage.

Valvular heart diseases are manifested into heart sound signal much earlier than they cause serious damage to the heart [Ahlstrom et al., 2006]. It is because the genesis of the heart sound components is related to the movement of the heart valves [Cherif et al., 2010]. Thus, by proper interpretation of the heart sound signal preventive measures could be taken timely to correct the disorder before the condition worsen. Moreover, such diseases may not be detected in the other cardiography signal such as ECG [Safara et al., 2013; Hu et al., 2014]. Because these defects do not alter the electrical depolarization of the myocardium and, hence, they are not reflected in the electrical activity of the heart [Hu et al., 2014]. These merits of the heart sound signal motivated us to analyse it for the diagnosis of CVDs at an early stage.

Diagnostic Characteristics of Heart Sound

CVDs impact the acoustical characteristics of the FHS in terms of intensity, time duration, and spectral content [Naseri and Homaeinezhad, 2013]. In addition, many pathological conditions can be diagnosed by analysis of an extra sound, called as a murmur [Yuenyong et al., 2011; Shen et al., 2013].

The heart rate can be derived from the timing information of the FHS and it can be used for diagnosis of abnormalities in heart rate such as bradycardia (heart rate <60) and tachycardia (heart rate>100) [Keong, 2004]. In patients with stiff left ventricles (hypertrophied), the intensity of S1 will be lower than normal one. It is because the atrioventricular valve leaflets forced shut from a shorter distance due to higher ventricular diastolic pressure. In severe aortic or pulmonic stenosis, the valve leaflets are less mobile and consequentially decreases the intensity of S2. In pulmonary arterial hypertension, the diastolic pressures in the aorta and pulmonary artery are greater than normal. This increases the velocity of blood flow back towards the valves and consequentially strengthens the intensity of S2 [Keong, 2004].

Murmurs are pathological sounds produced by the turbulent blood flow caused by structural defects of the heart such as narrowing of a valve (stenosis) or leakage in a valve (regurgitation) [Gradolewski and Redlarski, 2014; Debbal and Bereksi-Reguig, 2008a]. Stenosis is caused by the stiffness of heart valves, which restricts proper blood flow and regurgitation is condition of improper closing of the valves and causes blood to flow in the opposite direction to the normal [Boutana et al., 2011]. Murmurs are characterised by their timing, intensity, pitch, shape, and location. Timing refers to whether the murmur occurs during systole, diastole or is continuous throughout the cardiac cycle. Aortic Stenosis (AS), Pulmonary Stenosis (PS), and Mitral Regurgitation (MR) cause systolic murmurs. On the other hand, diastolic murmurs occur due to Aortic Regurgitation (AR), Mitral Stenosis (MS) etc. Systolic murmurs, AS lies in the frequency band of 120-250 Hz, PS lies in 200-250 Hz, and MR lies in 300-400 Hz. MR can be classified from other two systolic murmurs, PS and AS, as with wider duration and higher frequency band. S1 also becomes quieter than normal, in case of MR [Yuenyong et al., 2011]. Whereas PS causes longer duration between aortic and pulmonary components of the S2, called as split S2. Splitting of S2 also may occur due to atrial septal defect and right bundle branch block (heart muscle cells for electrical conduction). Diastolic murmurs lie in 100-250 Hz. MS causes mid-diastolic murmur with louder S1 and causes a high frequency opening snap of 90-130 ms after the aortic component of S2 [Reed et al., 2004]. While AR is relatively louder than other diastolic murmurs. But more severe AR causes a lower intensity murmur with longer duration. Two other sound components, S3 and S4, in PCG signal rarely occur and may indicate abnormalities. Presence of S3 in a child is normal, while in adults

(Age > 35) it represents diastolic overload or cardiomyopathy [Beritelli and Serrano, 2007]. A pathological S3 is also referred to as a ventricular gallop. S4 occurs just after atrial contraction and it may be due to ventricular hypertrophy or pulmonary arterial hypertension [Beritelli and Serrano, 2007]. A louder and longer S4 is an indication of abnormality of the health of the heart [Beritelli and Serrano, 2007].

Clicks and Opening Snaps are also pathological sounds. Clicks are high frequency short duration signals and they are associated with the opening of the aortic and pulmonic valves. Normally clicks are heard within 40-120 ms after the first heart sound in the systolic phase of the cardiac cycle. Opening snaps are high frequency short duration sounds that occur during the diastolic phase of the cardiac cycle, shortly after the second heart sounds. Opening snaps are the sounds associated with the loud opening of the mitral or tricuspid valve.

Heart sound analysis also has shown promising results to detect the Coronary Artery Diseases (CAD) prior to a heart attack [Akay et al., 1991; Semmlow and Rahalkar, 2007]. CAD occurs due to the deposition of the plaques inside the coronary artery due to which the blood flow is restricted. The restriction of blood flow causes turbulent sounds.

1.6 CONTRIBUTIONS OF THE THESIS

Above sections have described the importance of analysis of the heart sound signal and requirement of frequent heart monitoring. PCG and SCG are the two existing systems, which have been used to analyse the heart sound signal [Hu et al., 2014]. PCG is the most widely used technique for the analysis of the heart sound signal. It uses a stethoscope to measure acoustic sounds produced by the movement of the heart. The stethoscope actually amplifies the acoustic sounds, and these amplified acoustic sounds are converted into an electrical form with the help of a microphone. Another technique is the SCG, which uses an accelerometer. Recently, the interest of the researchers has been increased to explore the use of SCG for various diagnostic purposes because of newly emerged MEMS-based accelerometers, which are small in size and low in weight. These dimensional features are favourable to the convenience of the subject and better attachment of it to the body.

In literature, various algorithms have been proposed to address the issues related to the PCG and SCG, but separately. The analysis of their performance simultaneously in the presence of noise is required to show their applicability in real-life scenarios. Therefore, performances of both the systems are analysed in various real-life scenarios.

1.6.1 Performance Analysis of the PCG and SCG Systems in Various Real-life Scenarios

To analyse the performance, both the PCG and SCG signals were acquired simultaneously in clinical and different real-life scenarios including meeting, walking, travelling, and market. These scenarios represent the most expected activities of the subject wearing the system. The acquired signals are analysed in the time, frequency, and time-frequency domains. Results show that both the techniques are able to acquire the FHS, in the clinical set-up. However, in real-life scenarios, many favourable features are observed in the SCG such as, it does not require a microphone, and dimensional features (small size and light weight) of its sensor are in favour of good attachment to the chest wall. These merits make the SCG signal more robust to noise as compared to the PCG signal, although a scope of significant improvisation in SNR of the signal is also observed. Moreover, in 'walking' scenario, there are extra components (noise) present in the SCG signal due to footsteps.

1.6.2 Adaptive Thresholding Method for Wavelet Transform Based Denoising of the Heart Sound Signal

In view of the requirement of a denoising method for the heart sound signal, in this thesis, a Discrete Wavelet Transform (DWT) based denoising algorithm has been presented. The main contribution of the work is to estimate the threshold value adaptively based on the statistical parameters of the signal under consideration. Moreover, a new threshold function, non-linear mid function is also proposed to address the issues in the existing threshold functions, soft and hard.

1.6.3 A Method for Cancellation of Motion Artefacts from the Seismocardiogram Signal

As discussed above, noise generated due to the footsteps while walking contaminates the SCG signal. The analysis of the signal in 'walking' scenario is more important as it is used to measure the heart's ability to respond to external stress. Therefore, a novel method is proposed to remove these contaminations from the SCG signal. For this purpose, a three-axis accelerometer was attached to the chest wall such that heart sound components are reflected in the z-axis while the motion noise due to footstep will be dominant in the x-axis signal. To remove the noise components from the heart signal (z-axis), the locations of footsteps from the x-axis are identified and the corresponding components from the z-axis are removed. After noise removal, FHSs are identified using Otsu's threshold method.

1.6.4 A Robust Algorithm for Segmentation of Heart Sound Signal using Tunable Quality Wavelet Transform

The proposed motion noise cancellation method and DWT based denoising algorithm suppresses the external noises efficiently and also murmurs in most of the cases. However, the need of improvisation was observed in the DWT based method for few pathological cases where the murmur overlaps the FHS significantly. This shortcoming of the method was due to the limitation of wavelet, in which the Q-factor (ratio of centre frequency to bandwidth) cannot be tuned according to the oscillatory behaviour of the FHS. To address the issue, in this chapter, we present a robust algorithm for the segmentation of PCG signal using Tunable Quality Wavelet Transform (TQWT), which provides the ability to tune the Q-factor and, hence, adequate separation of FHS and murmur can be achieved.

1.6.5 Assessment of Electro-mechanical Window using the Wearable Patch Based on SCG System

In this contribution, a portable device is developed using SCG and ECG for the assessment of Electro-Mechanical (E-M) window. Assessment of E-M window provides crucial diagnostic information about the health status of the heart. In tradition, PCG and ECG signals are acquired to assess the E-M window. However, the PCG needs improvisations in terms of size and weight of its sensor. Henceforth, a system is developed consists of circuit to acquire the SCG signal and ECG signal simultaneously. The locations of the sensors on the chest wall are identified and placed in such a way that all the sensors of the ECG and SCG are placed in a row and hence a patch like device is constructed. Such device would be convenient to the subject while wearing it for long term.

List of Publications

International Journals:

1. Puneet Kumar Jain and Anil Kumar Tiwari, "A robust segmentation algorithm for phonocardiogram signal using wavelet transform with tunable Q-factor", *Journal of Medical and Biological Engineering (SPRINGER)*, Vol. 37, pp.1-15, 2017.

2. Puneet Kumar Jain and Anil Kumar Tiwari, "An adaptive thresholding method for the wavelet based denoising of phonocardiogram signal", *Biomedical Signal Processing and*

Control (ELSEVIER), Vol 38, PP. 388-399, 2017.

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1.7 THESIS OUTLINE

The organization of the thesis is as follows:

Chapter 2 Chapter 2 provides the review of the existing portable cardiography systems in terms of their suitability for use in real-life scenarios.
Chapter 3 In this chapter, performance analysis of the PCG and SCG systems is provided in various real-life scenarios.
Chapter 4 This chapter presents the proposed DWT based denoising method and a motion artefacts removal method.
Chapter 5 Chapter 5 provides the proposed segmentation algorithm for heart sound signal using tunable-quality wavelet transform.
Chapter 6 The developed system architecture for the assessment of electro-mechanical window using SCG is presented in this chapter.
Chapter 7 Concluding remarks and future works are discussed in Chapter 7.

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