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Wavelet Transform Based Abnormality Analysis of Heart Sound

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***Abstract*-This paper is concerned with the analysis of the first (S1) and second (S2) heart sound of the Phonocardiogram signal (PCG) using Discrete Wavelet Transform (DWT) and Continuous Wavelet Transform (CWT). The second heart sound S2 consists of two major components A2 and P2. The time delay between them plays very vital role in medical diagnosis. DWT is used for denoising and finding the best split of A2 and P2 components of S2, where as, CWT is used to determine the number of frequency components of S1 and S2. Experiments are performed on normal and pathological PCG signals. Denoising and finding split between A2 and P2 is carriedout using DWT. The frequency components of S1 and S2 of PCG are determined using CWT. Also split between A2 and P2 have been measured using CWT.**

Keywords- Heart Sounds, Wavelet Transform, Phonocardiogram.

I. INTRODUCTION

The mechanical activities of the heart during each cardiac cycle produce the sounds, which are called heart sounds. The factors involved in the production of heart sounds are as follow:

1. The movement of the blood through the chambers of the heart
2. The movements of cardiac muscle.
3. The movement of the valves of the heart.

The heart sounds can be heard by placing the ear over the chest or by using a stethoscope or microphone. These sounds can also be recorded graphically [1, 2]. Human heart generates four sounds during its activity for one cardiac cycle. These sounds identified as S1, S2, S3 and S4 are not all audible [3].

A phonocardiogram (PCG) is a display of the heart sound signal showing that heart sounds and murmurs can provide useful information to the physician by complementing cardiac auscultation. The major PCG clinical drawback is that it does not present information on frequency of heart sounds and their components [4, 9]. Heart sound analysis by auscultation is still insufficient to diagnose some heart diseases. It does not enable the analyst to obtain both qualitative and quantitative characteristics of the PCG signals. In addition to the first and second sounds, abnormal heart sounds may contain murmurs and aberrations caused by different pathological conditions of the cardiovascular system. Moreover, in studying the physical characteristics of heart sounds and human hearing, it is seen that the human ear is poorly suited for cardiac auscultation. Therefore, clinic capabilities to diagnose heart sounds are limited. The characteristics of the PCG signal and other features such as location of S1 and S2, the number of components for each sound, their frequency content, their time interval, all can be measured more accurately by digital signal processing techniques. The Discrete Wavelet Transform (DWT) is used for denoising [6, 7]. However the split can not be measured using DWT. The Continuous Wavelet Transform (CWT) provides the duration between the split of A2 and P2. Since heart sounds exhibit marked changes with time and frequency, they are therefore classified as non-stationary signals. To understand the exact features of such signals, it is thus important to study their time-frequency characteristics. In this paper the DWT have been used for denoising and finding the best split between A2 and P2. This is produced due to closer of aortic and pulmonic valves. The CWT is used to measure time delay between the component A2 and P2 for the second heart sound for the normal and pathological PCG.

This paper is organized as follows: Section II presents the processing of heart sounds using DWT and CWT. Experimental analysis of normal and various pathological heart sounds using above techniques have been presented in Section III. Finally the conclusions have been given in Section IV.

II. Processing of Heart Sounds

2.1 Wavelet Transform

A wavelet allows one to do multi-resolution analysis, which helps to achieve both time and frequency localization. Wavelet algorithms process data at different scales or resolutions. If we look at a signal with a large window, we would notice gross (or averaged) features. Similarly, if we look at a signal with a small window, we would notice detailed features. Thus, by using varying resolution, it solves the problem that was there with Short Time Fourier Transform (STFT), due to the use of fixed window size (or resolution) [10]. Wavelet Transform (WT) is of two types Continuous and Discrete.

2.2 Continuous Wavelet Transform

Continuous Wavelet transform is the alternative approach to the STFT [10]. WT has become well known as useful tools for various signal processing applications because of its good time-frequency resolution. CWT is best suited for signal analysis. Wavelet transform consist of computing coefficients

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that are inner products of the signal $x(t)$ and a family of "wavelets".

Continuous wavelet transform can be formally written as:

$$\Psi_x^{\psi}(\tau, s) = \int x(t)\psi^*_{s,\tau}(t)dt, \qquad (2)$$

where $\psi_{(s,\tau)}(t)$ is called wavelet function.

The variables s and τ are scale and translation parameter respectively.

The wavelets are generated from a single basic wavelet $\psi(t)$ (that satisfies the following properties), the so-called mother wavelet, by scaling and translation:

$$\psi_{(s,\tau)}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-\tau}{s}\right), \qquad (3)$$

The factor $s^{-1/2}$ is used for energy normalization across the different scales.

Wavelet function in CWT should satisfy the following properties:

Admissibility Condition:

$$C_{\psi} = \int_0^{\infty}\left|\frac{\Psi(\omega)}{\omega}\right| d(\omega) < \infty, \qquad (4)$$

where $\Psi(\omega)$ is the FT of $\psi(t)$. This condition ensures that $\Psi(\omega)$ goes to zero as quickly as $\omega \to 0$.

Zero average: It is normalized which means $\|\psi\| = 1$ and is centered in the neighborhood of $t = 0$ i.e.

$$\int_{-\infty}^{\infty} \psi(t)dt = 0. \qquad (5)$$

Unit energy: Wavelet function should have unit energy.

$$\int_{-\infty}^{\infty} |\psi(t)|^2 dt = 1. \qquad (6)$$

In short wavelets have zero average, unit energy and have fast decay. This means that $\psi(t)$ is wave for short duration and hence the name wavelet. If $\psi(t)$ is a real wavelet, then the resulting $\Psi_x(s,\tau)$ is called a real WT, measures the variation of $x(t)$ in a neighborhood of τ whose size is proportional to scale s. A real WT maintains an energy conservation principle, as long as the wavelet satisfies admissibility condition [10].

2.3 Discrete Wavelet Transform

The CWT described in the last section has redundancy. CWT is calculated by continuously shifting a continuously scalable function over a signal and calculating the correlation between them. It is clear that these scaled functions will be nowhere near an orthonormal basis and the obtained wavelet coefficients will therefore be highly redundant. To remove this redundancy Discrete Wavelet Transform (DWT) is used. In DWT the scale and translation parameters are chosen such that the resulting wavelet set forms an orthogonal set, i.e. the inner product of the individual wavelets $\psi_{s,\tau}$ are equal to zero. Discrete wavelets are not continuously scalable and translatable but can only be scaled and translated in discrete steps. This is achieved by modifying the wavelet representation as

$$\psi_{j,k}(t) = \frac{1}{\sqrt{s_0{}^j}}\psi\left(\frac{t - k\tau_0 s_0^j}{s_0^j}\right) \qquad (7)$$

Here j and k are integers and $s_0 > 1$ is a fixed dilation step and τ_0 depends on the dilation step. The effect of discretizing the wavelet is that the time-scale space is now sampled at discrete intervals. We generally choose $s_0 = 2$ so that the sampling of the frequency axis corresponds to dyadic sampling. For the translation factor we generally choose $\tau_0 = 1$. In that case the Equation becomes:

$$\psi_{j,k}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t - k2^j}{2^j}\right) \qquad (8)$$

One of the efficient ways to construct the DWT is to iterate a two-channel perfect reconstruction filter bank over the lowpass scaling function branch. This approach is also called the Mallat algorithm [10]. DWT theory requires two sets of related functions called scaling function and wavelet function and are given by:

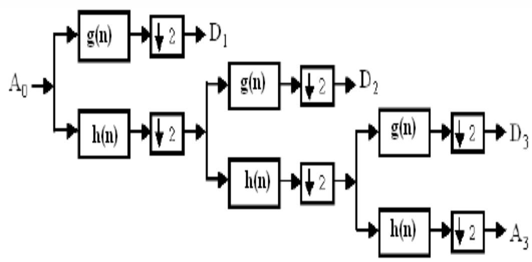
$$\phi(t) = \sum_{n=0}^{N-1} h[n]\sqrt{2}\phi(2t-n) \qquad (9)$$

$$\psi(t) = \sum_{n=0}^{N-1} g[n]\sqrt{2}\phi(2t-n) \qquad (10)$$

Where, function $\phi(t)$ is called scaling function and $\psi(t)$ is called wavelet function, $h[n]$ is an impulse response of a low pass filter and $g[n]$ is an impulse response of a high pass filter.

2.4 Signal Decomposition Using Wavelet Transform

The scaling function and wavelet functions can be implemented using pair of simple low pass and highpass filters. If the filters are interpreted with their impulse responses as $\{h(n), n \in N\}$ for a lowpass filter and $\{g(n), n \in N\}$ for a highpass filter, then the decomposition of a signal using DWT will be as shown in Fig 1. This decomposition is also called as dyadic decomposition. First stage divides the frequency spectrum into two equal parts (lowpass and highpass). The second stage then divides the lowpass band into another lowpass and highpass band .The second stage divides the lower half into quarter and so on.



h(n) = impulse response of low-pass filter , A-Approximate Coefficients,
g(n) = impulse response of high-pass filter, D-Detail Coefficients ,
↓2 -Down sampling by factor 2

Fig 1: Signal decomposition using DWT.

III. Results and Discussion

Normal and Pathological PCG signals were analysed using DWT and CWT techniques. PCG signals were recorded using electronic stethoscope. The sampling rate used was 8000 samples/s. Various pathological conditions such as aortic stenosis, pulmonic stenosis, atrial septal defect were consider for analysis.

3.1 Discrete Wavelet Transform Analysis of the PCG

DWT algorithm is applied on the PCG signal for both normal and pathological to determine the best split between the A2 and P2 of second heart sound. In order to identify the S1 and S2 correctly, we need to consider its main features in the time and frequency domains. The longest time interval between two adjacent peaks is the diastolic period which extends from the end of the S2 to beginning of S1 [3]. Fig.2 shows the six levels DWT decomposition of normal PCG signals. It shows the approximate components at six level as well as detail components d_1 to d_6. The decomposition is done using 6^{th} order Daubechies wavelet (db6).

The frequency spectrum of S1 is generally dominant in the range 10-200 Hz while the frequency spectrum of S2, 50-300 Hz [8]. The combination of time frequency properties is quite valuable in the identification of the S1 and S2. The signal has the sampling frequency of 8000 Hz. Approximate component a_6, and detail component d_6, to d_1 correspond to different frequency bands obtained from the DWT decomposition of the signal. The 6^{th} level approximation component a_6 corresponds to a frequency band 0 to 125 Hz. The 6^{th} level detail component d_6 correspond to the 125 to 250 Hz, 5^{th} level correspond to 250 to 500 Hz, 4^{th} level corresponds to 500 to 1000 Hz , 3^{rd} level correspond to 1000 to 2000 Hz , 2^{nd} level correspond to 2000 to 4000 Hz, while 1^{st} level detail correspond to 4000 to 8000 Hz. So from the plot of DWT components we can easily identify the corresponding frequency component of the first and second heart sound. From the observation of a_6 plot, S1 and S2 are clearly detected in that range having frequency band of 0-125 Hz. In addition to the normal heart sound we have carriedout the analysis of the heart sound with abnormalities like aortic stenosis, atrial septal defect, and pulmonic stenosis.

Fig.2 shows the DWT plot of the normal heart sound where the S1 and S2 are clearly dominant in the frequency range of the 0-125 Hz and 125-250 HZ. The oscillations of the S1 and S2 are clearly seen at a_6 and d_6 it mean that the frequency of the signal lies in the range of the band in which the first peak is the S2 and the second peak is the S1 [3].

Fig.3 shows the case of the Aortic stenosis in which both the heart sounds are affected due to which the high frequency components are generated. The S1 is depicted clearly at the d_6 level while S2 with its split is seen clearly in the a_6 level. The high frequency components are seen at the d_5 level in DWT plot. Due to abnormality in the signal it duration is also increased and sound is prolonged along with high frequency components.

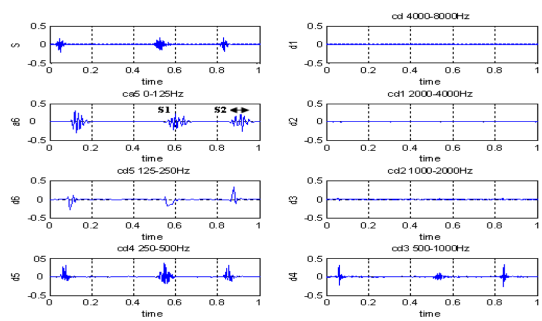


Fig.2 DWT of the Normal Heart sound

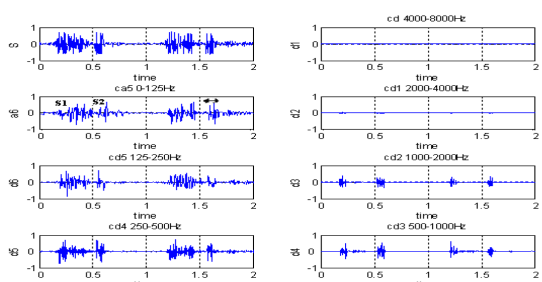


Fig.3 DWT of the Aortic Stenosis Heart sound

Fig.4 is the case of the Pulmonic stenosis in which the high frequency components are clearly seen in (d_5 and d_6) the systolic area due to the improper opening of the pulmonic valve. These frequency components are generated due to the pulmonic stenosis in the range of the 250-500 Hz .These high frequency components are seen at the d_5 level and actual heart sound are seen at the a_6 level in which the amplitude of the first heart sound is also affected as compare to the normal heart sound. Its amplitude should be larger than the second. The split is also clearly seen at the a_6 level of the second heart sound.

Fig 5 is the case of the Arterial septal defect. This is due to a hole between left and right atrium and due to this there is mixing of the oxygenated and deoxygenated blood hence the artrioventricular valve are not operating properly and affect on the heart sounds producing prolonged sound with high frequencies of the range 250-500 Hz. These are seen in d_5 and d_4 clearly.

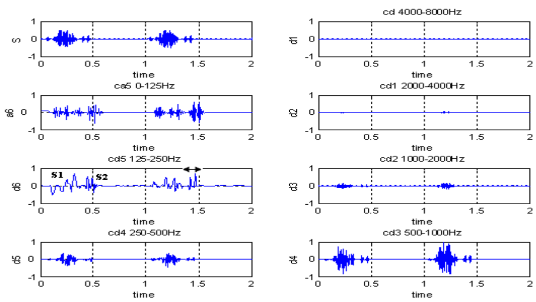


Fig.4 DWT of the Pulmonic Stenosis Heart sound

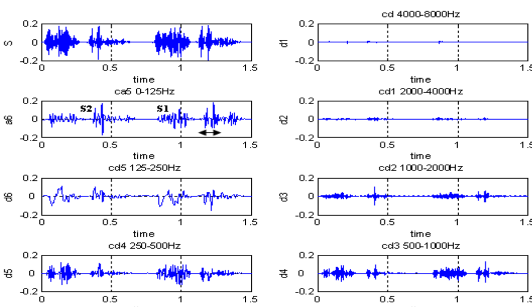


Fig.5 DWT of the Atrial Septal Defect Heart sound

From above experimental result of the DWT it can be concluded that:

- For the normal heart, the first heart sound depicts in the normal frequency band of 0-125 Hz, and 125 – 250 Hz (some times if signal present above 125 Hz). In the abnormal heart sound as it is having the higher frequency component and noise due to abnormality they are eliminated in the higher frequency band as shown in the results using DWT. So DWT gives the exact frequency band and split of S2.
- For the normal and pathological PCG signal the best split has been determine. It is shown in the specific frequency band of DWT. It is marked with arrow in a_6 band of fig. 2,3 5 and d_6 band of fig. 4.

The application of the DWT on heart sounds S1 and S2 after their identification shows the basic frequency spectral components. It also shows the split between A2 and P2. This is important in the diagnosis of heart sound. Here it is difficult to measure time split between A2 and P2 using DWT. To overcome this limitation CWT is used.

3.2 Continuous Wavelet Transform Analysis of the PCG

An algorithm of the CWT was applied to analyse the PCG signal of a normal cardiac cycle illustrated in Fig.6 (a). The two heart sounds were clearly shown in dark colour in Fig.6 (a). There was space of 2400 samples corresponding to 0.3 seconds. The CWT of S1 and S2 were also shown separately in Fig.6 (b) and Fig.6 (c) respectively. As it is shown in Fig.6(c), the sound S2 have higher frequency content than that of the S1. This is expected since the amount of blood present in the cardiac chambers is smaller [1]. The spectrum of S1 is clearly resolved in time in Fig.6 (b) into four major components. The spectrum of the sound S2 is resolved (in time Fig.6 (c)) into two major's components A2 and P2. The time delay between A2 and P2 can be easily measured (from Fig.6 (c)) using wavelet coefficients. This measured delay was 9ms. It was smaller than the 30ms as seen in the normal conditions of the PCG signal. In pathological condition this time difference is widen. The wavelet transform allows measurement and determination of this time difference and thus allows a diagnostic process regarding this important parameter to be produced. Here the one normal and three pathological cases i) aortic stenosis ii) pulmonic stenosis and iii) atrial septal defect as shown in Fig.7, Fig.8, and Fig.9 respectively were considered.

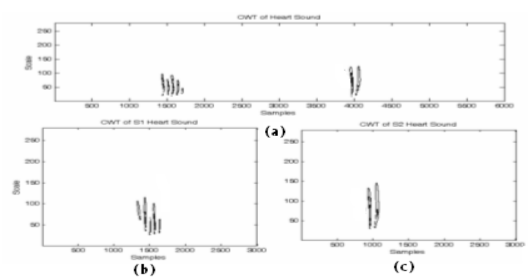


Fig.6 Coefficient of the CWT for the Normal Heart sound (a) One cardiac cycle (b) sound S1 (c) sound S2

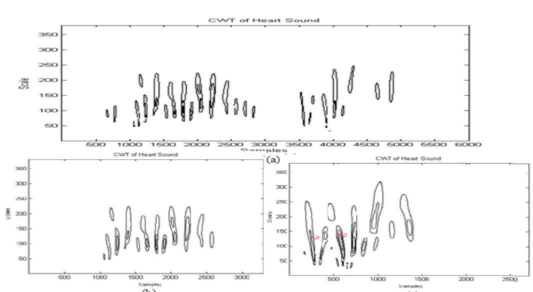


Fig.7 Coefficient of the CWT for the Aortic Stenosis (a) One cardiac cycle (b) sound S1 (c) sound S2

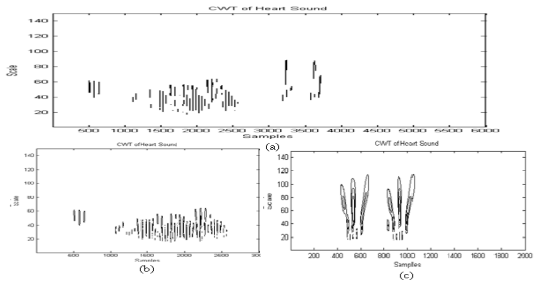


Fig.8 Coefficient of the CWT for the Pulmonic Stenosis (a) One cardiac cycle (b) sound S1 (c) sound S2

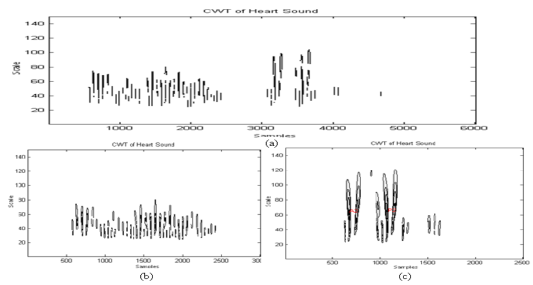


Fig.9 Coefficient of the CWT for the Atrial Septal Defect (a) One cardiac cycle (b) sound S1 (c) sound S2

3.3 Split Measure of S2

As specified in above sub-section that A2 and P2 of the S2 produced due closer of aortic and pulmonic valve, its time difference is very important for diagnosis of heart valves. The time difference between these two components in case of normal case is less than 30ms. But in abnormal cases it may become wide [8]. In normal case the dominant components were clearly seen representing A2 and P2 using CWT and its time difference was 9ms, which is less than 30ms. Hence from above three cases the time difference between A2 and P2 was more than 30ms due to abnormality. Pathological cases have more frequency components. The time delay between A2 and P2 for normal and different pathological cases is tabulated in Table 1.

Table1: Split time for normal and pathological conditions

Type of Signals	Normal	Aortic Stenosis	Pulmonic Stenosis	Atrial Septal Defect
Split(ms)	9	42	46	49

From above experimental results of the CWT it can be concluded that:

- In S2 two frequency components have been produced due to closer of the aortic (A2) and pulmonic (P2) valve and were clearly detected using CWT.
- For normal heart the time interval between A2 and P2 is less than the 30ms and for pathological case the time interval between A2 and P2 is larger than the 30ms and is measured easily.

IV. CONCLUSION

Abnormality analysis of heart sound using wavelet transform is presented in this paper.

DWT has been used to determine the best split between A2 and P2 of the second heart sound. Frequency component of each heart sound is determined using DWT. Using DWT it is impossible to determine the time split between A2 and P2 which plays vital role in diagnosis of the PCG signal. This drawback of the DWT is over come using CWT. The time delays between A2 and P2 have been measured using CWT. It is observed that the time delay between A2 and P2 is less than 30ms for normal case and it is greater than 30ms for pathological cases. With the developed Software, it is easily possible to identify whether the person is normal or abnormal with valves condition. This works as a good tool to help doctors to take decision for diagnosis of various diseases related with heart valves.

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