Smart Phone Monitoring of Second Heart Sound Split

Shanti R Thiyagaraja, Jagannadh Vempati, Ram Dantu, Tom Sarma, and Siva Dantu

Abstract— **Heart Auscultation (listening to heart sounds) is the basic element of cardiac diagnosis. The interpretation of these sounds is a difficult skill to acquire. In this work we have developed an application to detect, monitor, and analyze the split in second heart sound (S2) using a smart phone. The application records the heartbeat using a stethoscope connected to the smart phone. The audio signal is converted into the frequency domain using Fast Fourier Transform to detect the first and second heart sounds (S1 and S2). S2 is extracted and fed into the Discrete Wavelet Transform (DWT) and then to Continuous Wavelet Transform (CWT) to detect the Aortic (A2) and the Pulmonic (P2) components, which are used to calculate the split in S2. With our application, users can continuously monitor their second heart sound irrespective of ages and check for a split in their hearts with a low-cost, easily available equipment.**

I. INTRODUCTION

The heart sound can be heard using Auscultatory method, usually with a stethoscope. The sound can be characterized into *lub* (first heart sound) and *dub* (second heart sound). The first heart sound (S1) is produced by the closure of mitral valve (M1) followed by tricuspid valve (T1). Similarly, the second heart sound (S2) is created by the closure of the aortic valve (A2) followed by pulmonic valve (P2). This paper will focus on analyzing the second heart sound and its components.

The time delay that occurs between A2 and P2 is known as split or the "hangout interval". Analyzing the split and the relative intensities of A2 and P2 indicate the presence of cardiac abnormalities such as pulmonary stenosis and atrial septal defect. During inspiration, the interval between A2 and P2 widens (splitting). Normally A2 precedes P2 by 0.02 to 0.08 second (mean, 0.03 to 0.04 sec). With expiration, the interval shortens and has an average of 0.04 second [1]. If the split is greater than 0.04 seconds during expiration, it's considered as a pathological case.

The interpretation of the auscultation signal is subjective and depends on the skills of the health professional. It's often difficult to quantify the heart sound properties, especially when the split is in milliseconds. Hence, effective methods such as a digital signal processing tool are required to obtain a reliable diagnosis of the heart sound.

The wavelet transforms have been frequently used to extract features from heart sounds. The wavelet transform is a technique which provides time-frequency representation by decomposing a signal. This technique is proven to be capable of analyzing the heart sounds [2]–[4]. Furthermore, the wavelet transform performs more accurately than other techniques such as short-time Fourier transform and Wigner distribution in detecting A2 and P2 [5], [6].

Studies have been carried out on detailed analyses of the second heart sound for diagnosis of heart disease [7], [8]. However, the analysis of the heart sound cannot be performed outside the hospital environment. Monitoring heart disorder is essential for an individual as they should perform it on a daily basis. Continuous monitoring and analysis can provide a documentation of the cardiac events and improve health management. For example, Mendoza et al. [9] and Zhongwei et al. [10] proposed in-home monitoring of heart sounds. A wearable, battery-free tag monitor too was developed by Mandal et al. as low-cost device to monitor heart sounds [11].

We hereby propose a mobile phone based S2 analysis for split detection and monitoring with a low-cost, customized microphone attached to a stethoscope. The detection consists of three phases. The first phase involves recording of heart sounds using the customized stethoscope. The second phase comprises of processing the audio signal using wavelet transforms and identifying the A2 and P2 component. The third phase is to calculate the interval between the two components and display it for the user.

II. WAVELET TRANSFORMS

A. Continuous Wavelet Transform

The continuous wavelet transform (CWT) was developed as an alternative approach to the short time Fourier transform to overcome the resolution problem. CWT returns coefficients which is a measure of the similarity between the wavelet at a particular scale and time point and the signal at that instance. The CWT compares the signal to shifted and scaling or dilation of the wavelet. The Continuous Wavelet Transform (CWT) is defined as:

$$CWT_s(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} s(t)\Psi^* \frac{(t-b)}{a} \,\mathrm{d}t \qquad (1)$$

where
a is the scale parameter, $a > 0$

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b is the time parameter
$*$ denotes the complex conjugate
Ψ is the wavelet function used to analyze the signal
$s(t)$ is the signal

B. Discrete Wavelet Transform

Discrete wavelet transform (DWT) is a discrete analysis which provides sufficient information with a significant reduction in the computation time. The DWT of a signal S is calculated by filtering the signal with high-pass and low-pass filters, followed by subsampling by 2. The output of the high-pass filter is known as detail coefficients, the output of the low-pass filter is known as approximation coefficients. An iterative process of DWT 1 is called multilevel wavelet decomposition to further increase the frequency resolution.

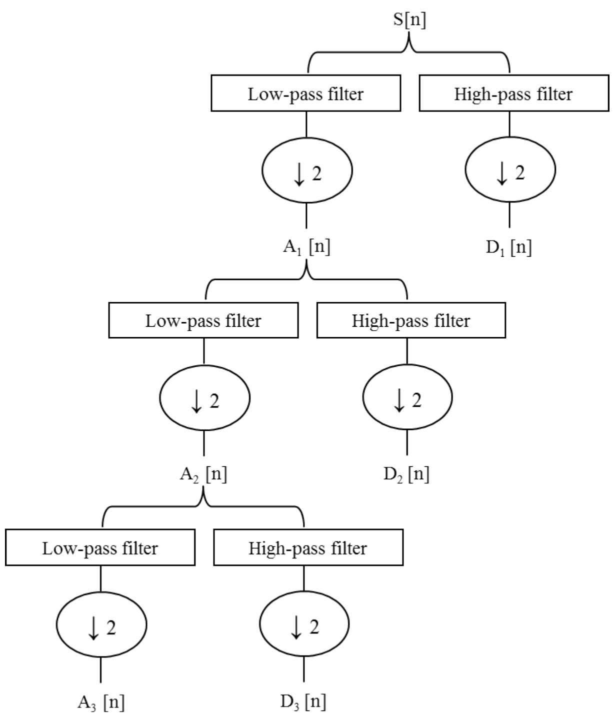

Fig. 1. Wavelet decomposition tree of 3 levels

III. METHODOLOGY

This section discusses the following processes in detail.

- Recording of heart sound
- Localization of first heart sound (S1) and second heart sound (S2)
- Detection of aortic (A2) and pulmonic (P2) components
- Calculation of split

A. Experimental Setup

The heart sounds are obtained using a customized external microphone connected to a Nexus 4 (Google Inc.) smart phone. The design of the external microphone consists of an acoustic stethoscope and 3.5m mini-plug condenser microphone with adapter. This setup has been used in our previous work [12].

B. Heart Beat Localization

The recorded heart sound is then converted into the frequency domain using fast Fourier transform. A normal heart sound signal has a frequency range of 40Hz to 200Hz where S2 has a higher frequency than S1. Once S1 and S2 are found, the S2 signal is extracted from the original signal. An example of S1 and S2 are shown in Figure 2.

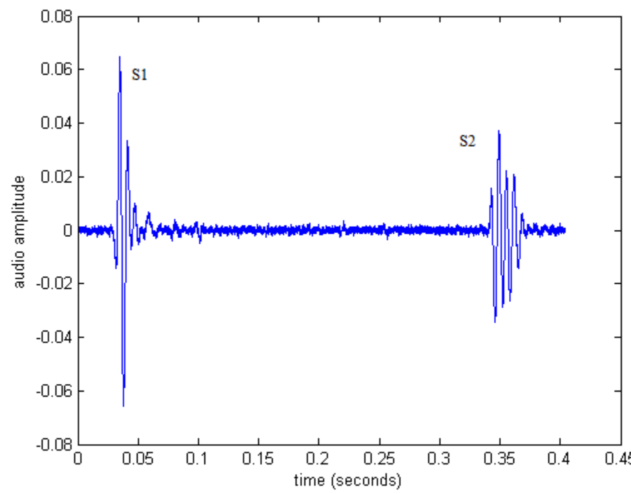

Fig. 2. A normal heart sound where the first and second heart sounds are identified

C. Localization of Components in Second Heart Sound

First, the S2 signal is applied with DWT. The signal is decomposed to 7 levels. Figure 3 displays the wavelet decomposition of the original signal. Level 7 shows approximation coefficients of S2 while level 1 to 6 show the detail coefficients of S2.

Next, CWT is applied to the approximation coefficients in level 7. Figure 4 and 5 plot the scalogram of the CWT coefficients in two-dimensional and three-dimensional respectively.

A2 contains higher frequency then P2 [3]. In the contour plot, if the range of scales is bigger, it contains a higher frequency. Based on Figure 4, A2 has an approximate scale range of 410 while P2 has an approximate range of 380. Thus, it can be concluded that A2 precedes P2 since the range of scale of A2 is larger than P2. Moreover, A2 has a higher coefficient (occurs at sample = 1290) than P2 (occurs at sample = 1439) which can be seen in Figure 5.

D. Split calculation

Once the two components of the S2 are detected, the time interval between them is calculated as in (2). The heart sounds are recorded at a sampling rate of 8KHz.

$$\text{S2 Split} = \frac{\text{Location of P2 - Location of A2}}{\text{sampling frequency}} \tag{2}$$

Since the locations of A2 and P2 are in samples, the difference in number of samples has to be divided by the

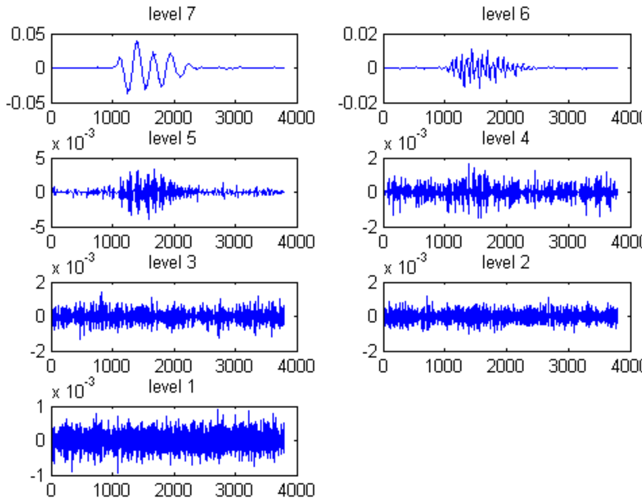

Fig. 3. Multilevel wavelet decomposition of a second heart sound. The *x-axis* is samples and *y-axis* is signal amplitude

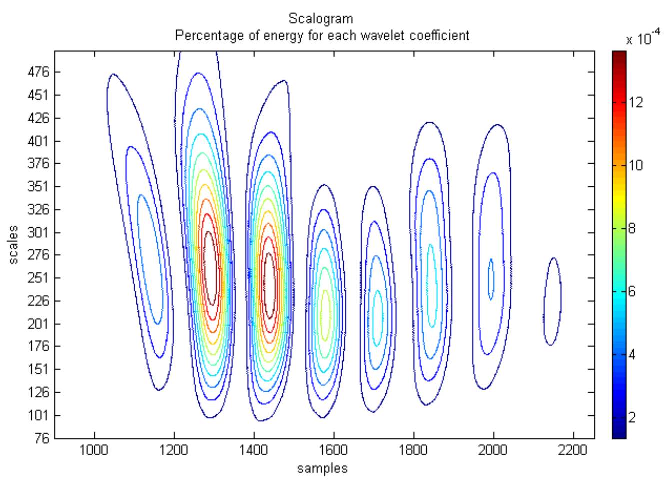

Fig. 4. Contour plot (two-dimensional) of continuous wavelet transform coefficients

sampling frequency of the audio signal in order to obtain the split in terms of seconds. The time delay between A2 and P2 in Figure 4 and 5 is 33.7ms. As the interval is smaller than 40ms, the S2 is concluded to be a normal heart sound.

IV. COMPARISON BETWEEN NORMAL AND ABNORMAL CASES

The heart sounds of 15 healthy subjects comprise of both male and female between an age of 21 and 28 years were obtained using the mobile phone and the customized microphone. 23 abnormal heart sounds were obtained from online databases and fed into the mobile phone. Part of the results obtained from the calculation of S2 split are tabulated in Table I. The 3 subjects are concluded to have normal S2. The split signals (last three in the table) are confirmed to

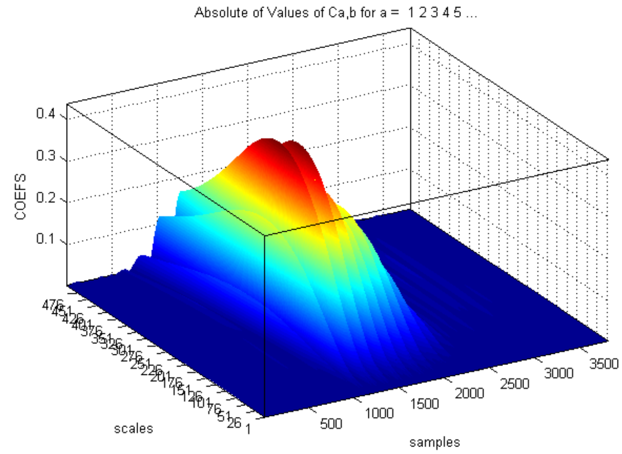

Fig. 5. Three-dimensional plot of continuous wavelet transform coefficients

have a delay of more than 40ms.

TABLE I

TIME DELAY BETWEEN A2 AND P2 FOR VARIOUS TYPES OF HEART SIGNAL

S2		Localization (ms)	Delay (ms)
Subject 1	A2	33.54	24.3
	P2	57.85	
Subject 2	A2	30.16	34.9
	P2	65.10	
Subject 3	A2	45.29	29.7
	P2	74.96	
Split 1	A2	36.30	53.4
	P2	89.73	
Split 2	A2	105.31	66.5
	P2	171.79	
Split 3	A2	40.75	59.7
	P2	100.45	

V. PERFORMANCE TESTING ON VARIOUS SMART PHONES

The application was deployed and tested on various smart phones. The time taken to analyze the second heart sound on different smart phones with varied processing power is tabulated in Table II.

TABLE II

TIME DELAY BETWEEN A2 AND P2 FOR VARIOUS TYPES OF HEART SIGNAL

Smart phone	Processing power	Time (s)
Samsung S3	Quad-core 1.4GHz Cortex-A9	26.15
Nexus 4	Quad-core 1.5GHz Krait	37.77
HTC One X+	Quad-core 1.7GHz	28.43

VI. CONCLUSION

We have presented a smart phone application for analysis and monitoring of second heart sound in this paper. The audio signals are recorded using a stethoscope attached to an external microphone. Then, the signal is interpreted using continuous and discrete wavelet transforms. This helps to identify the aortic and pulmonic components in second heart sound. Finally, the split (time delay between the two components) is calculated in order to classify the signals into normal and abnormal heart sounds.

The importance of this method is that it allows the users to monitor their heart sounds in any environment and on a daily basis. The users are able to document their health data and later share it to the health professionals. This also allows for easier health management from the user and health professionals' perspective.

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