

Heart Sound Measurement and Analysis System with Digital Stethoscope

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Abstract—This paper focuses on the heart sound measurement and analysis system for in-home use of heart condition monitoring. The heart sound acquiring system includes a traditional chest-piece, an earphone, a microphone and an IC recorder. The recorded data transmitted into a computer by USB interface are analyzed by the analytical model of single degree-of-freedom(SDOF) for extracting cardiac sound characteristic waveform(CSCW). Furthermore, the 4 characteristic parameters [T1, T2, T11, T12] related to the first heart sound (S1) and the second heart sound (S2) are defined by the time intervals between the crossed points of the CSCW and the threshold value (THV) line in order to discriminate normal and abnormal heart sounds. Meanwhile, an easy understanding graphical representation for these parameters is considered, so that inexperienced users are able to monitor their heart condition easily. Finally, the case study on 40 normal and 20 abnormal heart sounds from 10 healthy volunteers and 5 patients with heart disorders is carried out, the higher discrimination performances are achieved 92.5%, 95% in accuracy, respectively. The usefulness and efficiency of this proposed system and the CSCW method are demonstrated.

Keywords—Stethoscope; Heart sound; Measurement system; cardiac sound characteristic waveform(CSCW); Data processing

I. INTRODUCTION

Since 1985, the death due to heart diseases has become the second mortality after the stroke (cerebrovascular accident) in the world. At present, with the improvement of domestic living standards, numbers of patients with heart disease are increasing rapidly. Heart diseases associated with living conditions, such as coronary heart disease(angina pectoris, myocardial infarction) and hypertension are becoming more and more complex. If heart condition didn't get long-term and real-time monitoring and diagnosis, it may induce sudden heart disease and delay the best time to treat, even result in unpredictable grave consequences.

The studies on heart sound analysis has showed a rapid decrease after the 1970s because of the development of the techniques on the echocardiography and heart catheterization or percutaneous coronary intervention (PCI), which provide a closer and accurate examination^[1-2].

Recently, with the rapid development of computer hardware and digital signal processing, heart sounds could be recorded and analyzed easily, typical research^[3-8] on automatic

heart sound analysis showed new tendency. The majority of these researchers mainly emphasize on the characteristic extraction by frequency-analysis method. Others concern on how to extract the heart rate from a weeping infant through the heart sound signals, and improve signal-to-noise ratio by adaptive filtering way. Those researches were mainly concentrated on how to help the cardiologist get more accurate diagnosis.

Heart auscultation is one of the most fundamental ways to evaluate heart function, stethoscope can be used to auscultate respiratory sounds, lung sounds as well as heart sounds, and diagnose most of the cardiopulmonary disorders and other diseases. Therefore, it contains a lot of valuable information for the diagnosis of heart diseases.

However, using the stethoscope to diagnose human's disorders needs a long-term practice and experience. Even for a well-trained young cardiologist to auscultate and diagnose heart diseases, several years' clinical experience is required. Actually, an experienced cardiologist could hear out the pathologic heart murmur very sensitively but it is hard for an inexperienced doctor or a person without medical knowledge. Although the echocardiography and cardiac catheterization or PCI can provide an accurate diagnosis method, it needs high cost, and results in PCI trauma. Therefore, through heart auscultation to examine heart diseases is very important for ordinary health care, and the charge is low, even the ordinary household can afford it. If the heart sound could be recognized or diagnosed with the help of computer technique, the above problems will be solved, even for ordinary people without medical knowledge can also improve the ability to identify heart murmur by auscultation. The digital stethoscope is possible to become a high performance-price-ratio home medical and health care instrument, and enter into numerous households.

The purpose of this paper is to establish a novel heart sound measurement and analysis system for in-home heart disorder detection based on the traditional stethoscope. Firstly, heart sound acquisition can be achieved by using the traditional chest-piece auscultation, an earphone, a microphone and an IC recorder; Secondly, based on the cardiac sound characteristic waveform(CSCW) extracting

from the single degree-of-freedom(SDOF) model, we can analyze the collected heart sounds, meanwhile, easy-understanding graphs are considered. Furthermore, some clinical normal and abnormal heart sounds, which were collected by the heart sound acquiring system at hospital, are used to analyze the system and validate the CSCW method.

II. HEART AUSCULTATION

In the heart cycle, heart sounds are primarily generated from blood turbulence. The blood turbulence occurs due to fast accelerations and retardation of the blood in the chambers and arteries caused by the contraction or closure of the heart valves. The first heart sound (S1) and the second heart sound(S2) can be heard clearly in each heart cycle. S1 is generated at the end of arterial contraction, just at the onset of ventricular contraction, and also can be heard obviously in the interval of the fifth rib which lies in the midline of left clavicle. The main feature of S1 is low tone and long duration. S2 occurs during ventricular diastole and can be heard clearly at the auscultation region between aortic valve and pulmonary valve. In contrast with S1, it has characteristics of high tune and short time limit. S1 and S2 contain some information which plays an important in heart sounds auscultation. Certainly, sometimes, S3 and S4 can also be heard.

Heart sound frequency range is generally 5-600Hz, above 120Hz is usually considered as high-frequency sound, 80Hz-120Hz as middle-frequency sound, below 80Hz as low-frequency sound, detailed frequency distribution is shown as follows:

S3 and S4:10-50Hz; S1 and S2:50-100Hz; diastolic rumbling murmurs:40-80Hz, some even reach to 140 Hz; high-frequency murmurs (systolic and diastolic whiffing murmurs):100-600Hz, some up to 1000Hz; pericardial friction rub:100-600Hz^[9]

Heart sounds recorded by the stethoscope are shown in Fig.1. Normal heart sounds are shown in Fig. 1(a) shows Although some noise components are included, the first and second heart sounds can be seen clearly. Fig. 1(b) represents abnormal heart sounds of the mitral regurgitation. It is obviously showed that the noise is resulted from backflow of blood between the first heart sounds and second heart sounds.

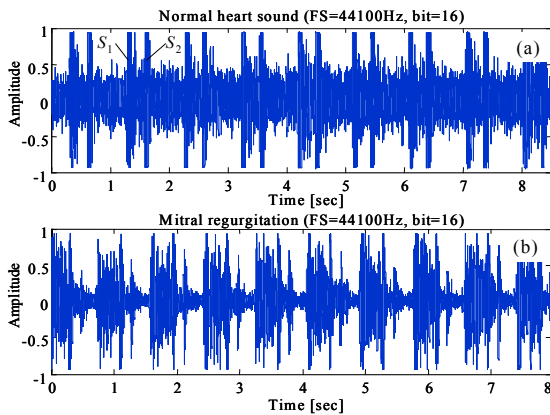


Figure 1. Heart sound examples (a) Normal sounds (b) Abnormal case of the mitral regurgitation

III. MEASUREMENT AND ANALYSIS

A. Heart sound recording system

The heart sound measurement and analysis system is researched and provided by Mechatronics Lab of Yamaguchi University of Japan. The heart sounds acquiring system, as shown in Fig. 2, is composed of a traditional chest-piece(Littman,ClassicIISE), an earphone, a microphone(audio-technical®, AT805F), an IC recorder (Olympus, Voice-Trek V-51). While auscultating heart sounds, you can also hear in the same time. The system adopt the normal standard chest-piece(Littman, ClassicIISE), which is used by many general doctors and is produced by American 3M company. The specifications of microphone and IC recorder are shown in Tab. I~II. The heart sound is recorded by IC recorder and then transmitted into a computer by USB interface. And then, they will be analyzed and displayed on the computer with the aid of MATLAB 7.1.

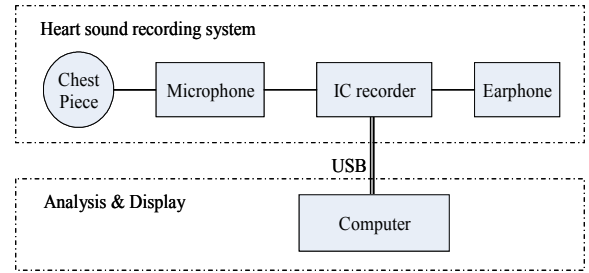


Figure 2. Block diagram of heart sound measurement and analysis system

TABLE I. SPECIFICATION OF THE MICROPHONE

Microphone(audio-technical®, AT805F)	
Frequency	30Hz -10,000 Hz
Sensitive(0dB=1V/Pa,1kHz)	-46 ± 3dB
Impedance	2kW

TABLE II. SPECIFICATION OF THE IC RECORDER

IC recorder(Olympus, V-51)	
Sampling Frequency	44.1kHz
Frequency	20Hz-20kHz
Bit rate	128kbps
Sampling Bit	16
Frequency	30Hz -10,000 Hz
Sensitive(0dB=1V/Pa,1kHz)	-46 ± 3dB
Impedance	2kW

B. Heart sound analytical program

The program based on MATLAB 7.1 programming environment, including deals the heart sound signal with the method of normalization and wavelet de-noising, extracts CSCW by SDOF, calculates parameters by a suitable threshold value(THV) line, and the easy understanding histogram and scattergram are used to describe. The program block diagram is shown in Fig. 3.

a) *Heart sounds acquisition*: Clinical data are acquired from patients at cardiovascular disease centre, the 452nd hospital of Chinese PLA, Chengdu, China. During the measurement, system parameters are set at the following conditions: 44.1kHz sampling frequency, high sensitivity, 8-12 seconds recording data length, and the patients are required to lie on the bed and keep calm breath during recording. Four clinical anatomical positions are: Aortic, Pulmonary, Tricuspid, Mitral. The recorded heart sounds are stored in the IC recorder for further processing.

b) *Pre-processing*: Heart sounds are stored in IC recorder in the format of MP3. MP3 audio format should be converted into recognizable format which can be read by MATLAB before analysis. The data is de-noised by wavelet de-noising method to eliminate the interference of heart sounds, which may come from sloshing of patients' body, holding of stethoscope in some undesirable way, or hardware itself of the recording system.

c) *CSCW extraction*: The eardrum is much easy to capture the low-frequency sounds and its durative time. In fact, any untrained user can use stethoscope to hear the metrical voice 'lub-dub' in normal heart sounds and 'whooshing' from mitral regurgitation^[10]. Based on this consideration, a vibration model of single degree-of-freedom (SDOF) is proposed to extract the duration of the sound acted on the eardrum for extracting CSCW.

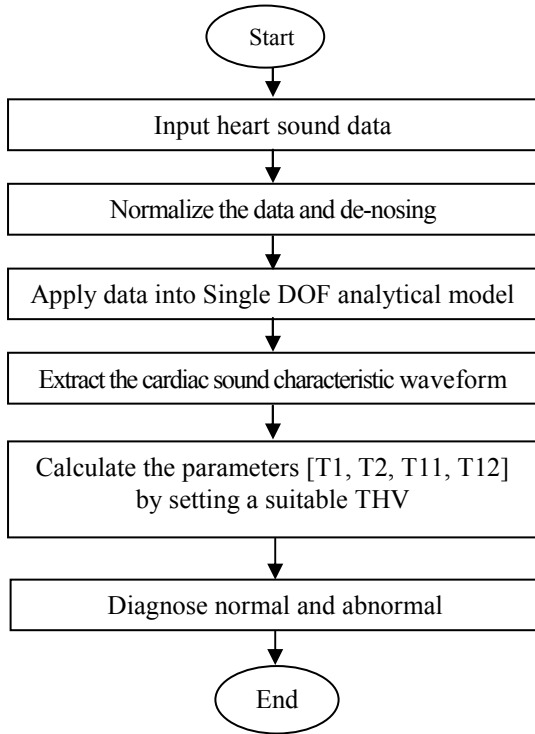


Figure 3. Block diagram of program used for heart sound analysis

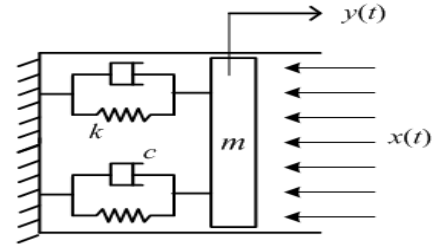


Figure 4. Schematic diagram of SDOF analytical model

Fig. 4 shows the schematic diagram of SDOF analytical model. Suppose that the mass, spring coefficient, damping coefficient in this model are m , k , c , respectively. Setting the heart sound recorded by the stethoscope as the input $x(t)$ ^[11]. Thus, output response is then given by:

$$m\ddot{y} + c\dot{y} + ky = x \quad (1)$$

Let $\bar{S} = |x/m|$, $p = \sqrt{k/m}$ and $\xi = c/2\sqrt{mk}$

Equation (1) becomes to:

$$\ddot{y} + 2\xi p\dot{y} + p^2 y = \bar{S} \quad (2)$$

Here p and ξ are the parameters of the resonant frequency and damping ratio respectively. Parameters are set as $p/2\pi = 5$ -10Hz and $\xi = 0.7$ -1.2 to extract the characteristics of normal and abnormal heart sounds.

Fig. 5 shows the results obtained by applying the sound data to SDOF analytical model in Fig. 1. Output responses y is described in heavy line and it is also normalized for post-analysis. It is obviously that heavy lines give more simple and conspicuous representation than the original sound signal waveform (grey lines), and they are easy to be treated in post processing and data analysis. Thus, the waveform described in heavy line is called hereinafter as cardiac sound characteristic waveform (CSCW)^[11]. The next problem to be solved is how to define the parameters that could be used as diagnosis indicators for identifying the normal and abnormal heart sounds automatically with the aid of computer.

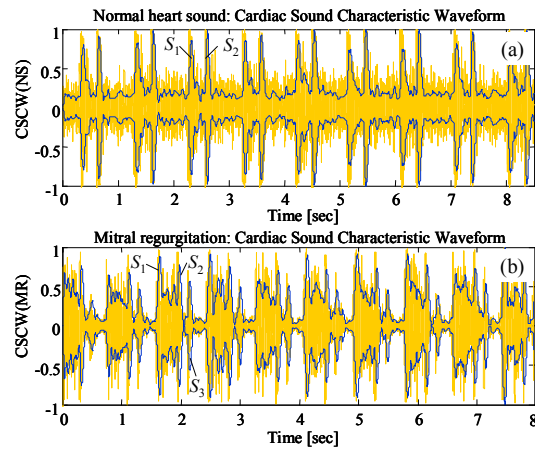


Figure 5. Plots of heart sounds(x) in Fig. 1 and their characteristic waveforms(y) obtained at $p/2 = 10$ Hz and $\xi = 0.7$ (a) Normal heart sound (b) Abnormal case of the mitral regurgitation

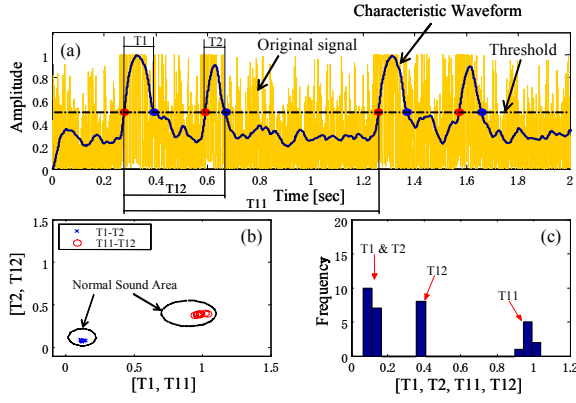


Figure 6. Definition of the characteristic parameters and their graphic representations (a) Definition of the characteristic parameters $[T1, T2, T11, T12]$ (b) The scatter gram and (c) the histogram of the parameters

d) *Definition of characteristic parameters and graphic representations:* As mentioned above, S1 and S2 play an important role in heart disease diagnosis. Therefore, a concept for defining characteristic parameters is described in detail in Fig. 6. Firstly, select a suitable line as threshold value (THV) line across with CSCW. The THV line could be selected dependently on the person individual or types of pathology. Secondly, $T1_i, T2_i, T11_i$ and $T12_i$ ($i = 1, 2, \dots, N_i$) defined as characteristic parameters by the time intervals between the crossed points of the CSCW and threshold line and are used for discriminating normal and abnormal heart sounds as shown in Fig. 6(a). $T1_i$ and $T2_i$ represent time intervals of S1 and S2 in the i th continuous data respectively. $T11_i$ is the time intervals of two adjacent S1 and is used for displaying heart beat rhythm status. $T12_i$ is time intervals between S1 and S2 and can be used as parameter for diagnosing heart valve murmur. In order to visualize $[T1_i, T2_i, T11_i, T12_i]$, two-dimensional scatter gram is showed by the corresponding relation of $[T1, T2]_i$ and $[T11, T12]_i$ in Fig. 6(b).

In general, a normal heartbeat cycle is about 0.8 seconds, the arterial contraction or ventricular systole $[T1, T2]$ is around 0.1 seconds, duration of the systolic and diastolic of whole heart sound is about 0.4 seconds. Assuming normal heartbeat rhythm area is represented by two circles. Radius size is determined by literatures ^[12-14], which centers are supposed at $[0.1, 0.1]$ and $[0.8, 0.4]$ as shown in Fig. 6(b). If the characteristic parameters $[T1, T2]_i$ and $[T11, T12]_i$ are calculated out belong to this two circles, heart sounds can be identified as normal. Therefore, users can understand their own heart sound condition clearly by the aid of scatter gram. Furthermore, in order to help users and doctors make effective quantitative evaluation, these parameters are also described in a histogram as shown in Fig. 6(c). The histogram could be helpful for both general users and doctors to monitor the heart pathology easily and discover the heart disorders in advance.

IV. CLINICAL VERIFICATION AND RESULT DISCUSSION

In this section, heart sound signal measurement and analysis system is validated effectively by normal and abnormal cases using CSCW method. At present, 40 cases of

normal heart sounds and 20 abnormal cases from 10 healthy volunteers and 5 patients were collected by this system (four clinical auscultation anatomical positions of every person were tested respectively: aortic, pulmonic, tricuspid, mitral). The normal heart sounds were collected from national defense students of Xihua University, who were strictly checked in the clinical examination. The abnormal heart sounds were from cardiovascular disease centre, the 452nd hospital of Chinese PLA, Chengdu, China. In order to compare and research in the same conditions, THV value was selected as 0.25, filter band: 229.68—918.75Hz, parameters of SDOF analytical model were: $\xi=0.707$, $p=10\text{Hz}$. The analysis results are showed in Tab. III. With the proposed CSCW method, the accuracy performances were achieved 92.5%, 95% respectively for discriminating normal and abnormal sounds.

TABLE III. ANALYTICAL RESULTS OF 40 NORMAL AND 20 ABNORMAL HEART SOUNDS

	Experiment numbers	Correct numbers	Wrong numbers	Accuracy
Normal	40	37	3	92.5%
Abnormal	20	9	1	95 %

Due to the limitation of paper length, a normal and an abnormal heart sound signal were selected and discussed in detail in the following. Normal heart sound signal was measured from a 20 years old male of 175cm height and 55kg in weight. His heart sounds were measured at pulmonary position. Fig. 7 shows the analysis result using the above methods, looking at the scattergram, the analysis parameters $[T1, T2]$ and $[T11, T12]$ are concentrated within the two discriminated circles. It indicates that the heart situation is normal

As shown in Fig. 8, an abnormal heart sound case, from a 45 years old female of 156cm height and 40kg in weight, diagnosed as rheumatic heart disease and mitral stenosis. From original heart sound waveform and CSCW curve, it is obviously showed that the noise between S1 and S2 disappeared because of the ventricular septal defect. Further, the plots of the analytical parameters $[T1, T2]$ and $[T11, T12]$ are scattered out of two normal circles as shown in the scattergram. Therefore, it is easy to understand that the heart sound is abnormal. In addition, from the histogram, we can see $T11$ value, which can be converted to the heart rate as $60/T11$, so abnormal heart rate can be monitored by this.

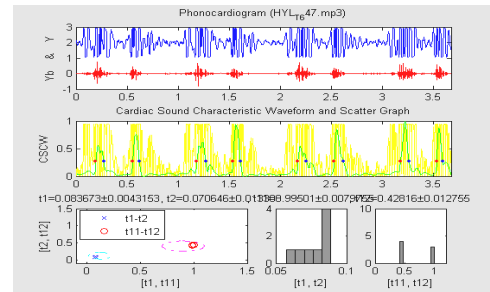


Figure 7. Normal heart sound analysis results

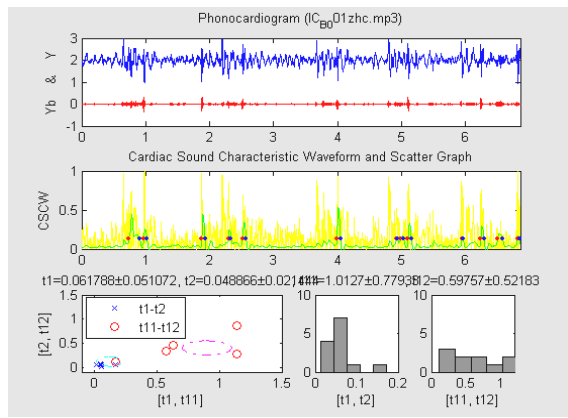


Figure 8. Abnormal heart sound analysis results

From Tab. III, during the 20 abnormal heart sound signal analysis results, there is a wrong case. The analysis results were showed in Fig. 9. The abnormal heart sound signal was recognized as aortic insufficiency in clinical examination, but it was distinguished as normal. Therefore some abnormal heart sound signal may be possible wrong distinguished. The elementary frequency-analysis experiments indicate that normal and abnormal heart sound signal had obvious different frequency band. Due to this, heart sound signal frequency-analysis is considered as concentrated research contents to improve the accuracy in the future.

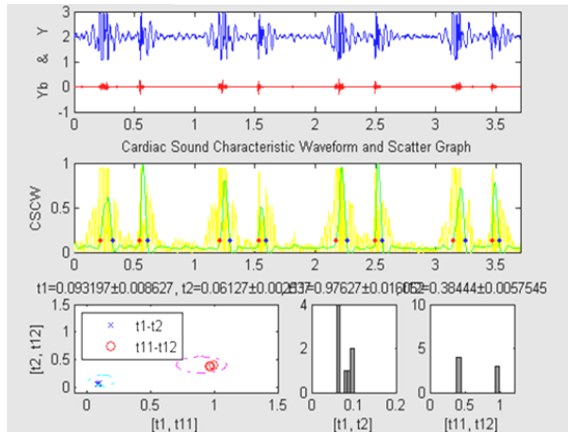


Figure 9. Aortic insufficiency analysis results

From the above description, we can draw a conclusion that the CSCW method provides an easy-understanding way to analyze heart diseases by simple curve graphs. Furthermore, 40 normal and 20 abnormal heart sound cases were tested and analyzed statistically, so as to verify the usefulness and efficiency of this proposed system and CSCW method. It provides a new method for discriminating normal and abnormal heart sounds. In addition, characteristic parameters are affected obviously by THV, how to choose a suitable THV automatically is a significant research content for intelligent analysis

Heart sound measurement and analysis system had been tested in clinical experiment. To improve the system performance, there are still lots of work to do. In the future, we are going to develop more high-quality heart sound waveform extracting technology, to establish individual heart sound database, and to improve discriminate accuracy rate by using frequency-analysis as a complementarity.

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