Multichannel Cardiac Sounds Measuring System for Monitoring Children’s Congenital Heart Disease at Home

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Recently, the need for primary health care becomes stronger for general users to perform at home. This study is to develop a multichannel cardiac sounds in-home measuring system for monitoring children’s congenital heart diseases (CHD). Children’s cardiac auscultation is always influenced by their hyperactivity or breathing loudly, in view of this circumstance, the multichannel measuring system with auscultation clothes and electronic stethoscopes is designed to obtain the multichannel cardiac signals simultaneously. Further, the multichannel signals analysis methods are proposed to extract the diagnosis features, which are heart rates by characteristic moment waveform in time domain, frequency width by AR-PSD in frequency domain and murmur index by WPE from energy analysis. These effective parameters are using for children’s parents and doctors to monitor disease state in simple and convenient way. This home health care system is verified to be useful and convenient for not only physicians but also general users.

Keywords: multichannel measuring system, auscultation clothes, analysis methods, children’s congenital heart disease monitoring, home healthcare, murmur index.

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1. Introduction

Congenital heart defects (CHDs) are problems with the heart’s structure or function those are present at birth. They affect 8 out of every 1,000 newborns [1]. But it is known this kind of defects can be cured with a high probability if the diseases could be detected in an early stage. For this reason, the research about early detection of CHD is one of the most important medical research areas [2]. Recently, the need for the primary health care becomes stronger for general users to perform at home. So it needs to develop cardiac sounds in-home measuring system for monitoring children’s CHD. The common CHD types were selected as the abnormal heart sound (AHS) materials.

The normal resting adult human heart rate (HR) ranges from 60 to 100 bpm. Infants’ HR is always higher than the normal range [3]. The abnormalities of HR sometimes indicate disease, so HR testing is necessary. Heart murmurs are pathological sounds produced by turbulent blood flow due to certain cardiac defects, and show their different characteristics in the frequency domain. Many researches have been concerning on the characteristic extraction by local frequency analysis methods [4-7]. The heart murmurs are the most common reasons for referral to the pediatric cardiologist. However, if the child is crying, uncooperative to the examiner or breathing loudly, it might cause some other murmurs.

Innocent and organic heart murmurs cannot be readily distinguished, so heart murmurs evaluation analysis is necessary. Recently, the demand for evaluation of the murmurs from auscultation of cardiac sounds has been addressed by researchers and clinicians [8-11]. Most of them are mainly concentrated on how to help the cardiologist having more accurate diagnosis.

The objective of this paper is to develop multichannel cardiac sounds in-home measuring system for monitoring children’s CHD. Children’s cardiac sound collection is always influenced by their hyperactivity and un-cooperation to the examiner or breathing loudly, the multichannel measuring system with auscultation clothes is designed to obtain the high quality cardiac signals. And the main work of this study is to design the monitoring system, which can implement functions for users to monitor the disease state though multichannel signals analytic parameters in simple and convenient way. The analysis methods are proposed from aspects of time domain analysis, frequency domain analysis and cardiac murmurs evaluation by signal energy analysis. Finally, the cases study on the normal heart sound (NHS) and AHS are demonstrated to validate the usefulness and efficiency.

2. Multichannel signals measuring system

Heart sound (HS) signals contain much more important physiological and pathological information, especially, the signals from different positions reflect different turbulence conditions created when the heart valves snap and shut. Clinical auscultation positions are always Aortic (A), Pulmonic (P), Tricuspid (T) and

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Mitral (M) areas, which is showed in Fig.1. Therefore, how to collect the high quality HSs simultaneously is a key point for HS measuring. Children’s cardiac auscultation is much more difficult than adults, therefore, the multichannel measuring system with auscultation clothes and electronic stethoscope is developed to obtain the HS from children. This measuring system is composed of a computer, four-channel physiological signal recorders that are composed by two IC recorders, the auscultation cloth with four stethoscope chest pieces and microphones, as shown in Fig.1. In addition, the frequency of microphone (audio technical®, AT805F) is from 30Hz to 10 kHz, and the sampling frequency of IC recorder (Olympus Voice-Trek V-75) is 44.1 kHz. This measuring system can be also used for healthy person at sports state. Here, Fig.2 and Fig.3 show two samples of clinical measured sound signals. Fig.2 is the case of healthy male student, who is measured lying in the supine in a quiet test room, and Fig.3 is measured from a patient who suffered Tetralogy of Fallot, and also be measured lying in the supine in the hospital patient room.

![Auscultation positions](image1)

![Auscultation cloth with stethoscope chest pieces and microphone](image2)

![Two IC recorders fixed by a plastic case](image3)

Fig. 1. Multichannel signals measuring system.

![Four-channel signals from normal person.](image4)

Fig. 2. Four-channel signals from normal person.

![Four-channel signals from a patient of Tetralogy of Fallot.](image5)

Fig. 3. Four-channel signals from a patient of Tetralogy of Fallot.

3. Signal analysis method

Firstly, the data pre-processing method for analysis of CHD is introduced in this paper. Secondly, the HR is obtained based on envelop waveform (EW) and characteristic moment waveform (CMW) of CHD signals. And then the feature frequency width (Fw) is extracted based on autoregressive power spectral density (AR-PSD) estimation curve. At last, cardiac murmurs indexes (MI) are evaluated based on wavelet packet energy (WPE) technique.

3.1 Pre-processing

The original HS signal \(x(t)\) recorded by measuring system with 16-bit accuracy and 44.1 kHz sampling frequency. Firstly, the recorded signal was converted into 20 kHz. Next, Daubechies10 (DB10) wavelet was used as a mother wavelet for the wavelet decomposition. The resulting signals with band limit of 20–625 Hz [13] were reconstructed by the components of d5 and d9. Finally, the normalization was applied by setting the variance of the signal within a value of 1.0. The resultant signals can be expressed as \(s(t)\).

3.2 Extract HR based on CMW

Suppose the heart sound signal \(s(t)\) added with the random noise signal \(n(t)\), and the measured signal is \(x(t)=s(t)+n(t)\). It is easy to express their variances by \(\sigma^2(x)=\sigma^2(s)+\sigma^2(n)\). Since \(\sigma^2(n)\) is theoretically zero, the EW of the signal \(e(t, \delta)\) can be easily obtained by [12], where \(\delta\) is neighborhood of time \(t\), called the width \(\delta\) time scale, and then

\[
e(t, \delta) = \int_{t-\delta}^{t+\delta} (x(\tau) - \bar{x}(t))^2 \, d\tau \tag{1}
\]

\[
\bar{x}(t) = \frac{1}{2\delta} \int_{t-\delta}^{t+\delta} x(\tau) \, d\tau \tag{2}
\]

Further multi-scale moment of characteristic waveform \(l(t, \delta, l)\) of \(e(t, \delta)\) is defined as:
\[ I(t, \delta, l) = \int_{t-l}^{t+l} (\tau - t)^2 e(\tau, \delta) \, d\tau \]  
(3)

Normalization of the moment calculation Eq. (3) is stated as:

\[ n(t, \delta, l) = \frac{\int_{t-l}^{t+l} (\tau - t)^2 e(\tau - \delta) \, d\tau}{\int_{t-l}^{t+l} e(\tau - \delta) \, d\tau} \]  
(4)

Here, call \( n(t, \delta, l) \) as the characteristic moment of \( e(t, \sigma) \). In this study, \( \delta = 0.05 \) and \( l = 0.45 \). \( F_{\text{max}} = \text{max}(\text{fft}(n(t, \delta, l))) \), and \( \text{HR} = 60 \times F_{\text{max}}(b) \). \( F_{\text{max}} \) is the maximum frequency of CMW. EW and CMW curves are shown in Fig.4.

3.3 Obtain \( F_w \) based on AR-PSD estimation

Consider a data series \( s(t), t=1,\ldots,N \), is represented by a linear combination of previous value \( s(t-k) \) and a white noise input \( w(t) \). Hence, the AR model at order \( p \) is defined as follows:

\[ s(t) = -\sum_{k=1}^{p} a_k s(t-k) + w(t) \]  
(5)

In AR model, the AR-PSD estimation can be given by:

\[ P_{\text{AR}}(f) = T \sigma_w^2 \left| 1 + \sum_{q=1}^{p} a_q e^{-j2\pi f qT} \right|^2 \]  
(6)

\[ r_{xx} = -\sum_{q=1}^{p} a_q r_{xx} (t - q) \]  
(7)

Therefore, the results of the AR-PSD estimation could be calculated from \( a_q \) and \( \sigma_w^2 \). In this study, the threshold value (Thv) is set as 0.02, the frequency width (\( F_w \)) is extracted as a parameter, and the spectral curve is showed in Fig.5.

3.4 MI evaluation based on WPE

Heart murmurs have shown their different characteristics in different frequency ranges [14], the steps are introduced as follows. In order to evaluate the murmur at different frequency ranges, the resulting signals with band limit of 5-1250 Hz were reconstructed by the components from d11 to d4. At last, the normalization was applied by setting the variance of the signal within a value of 1.0. The resultant signal is expressed as \( \tilde{s}(t) \).

Considering the ranges of the innocent and pathologic murmurs in frequency domain, the wavelet packet decomposition at level 11 is employed to split frequency bandwidths of HS signals. Through clinical auscultation observation and energy intensity analysis at each level (d11–d4), the interested parts and useful combinations are implemented, and five frequency bands are defined and shown in Table 1. They are named as very low frequency (VLF), standard frequency (SF), low frequency (LF), middle frequency (MF) and high frequency (HF). Further the energy ratio at each range are expressed by

\[ \text{EP}(j) = \sum_i^N |\tilde{s}(i)|^2 / \sum_{j=1}^5 \left( \sum_i^N |\tilde{s}(i)|^2 \right) \]  
(8)

where \( j=1,\ldots,5 \). Their corresponding wavelet detail coefficient levels, center frequencies and energy ratios are represented in Table 1.

As showed in Table 1, the main energy of HS is concentrated at SF band and the pathologic murmurs represent the high energy density at LF, MF and HF bands. Based on this fact and our experimental trial and error, the evaluation indexes of cardiac murmurs (MI) are defined as the following:

\[ \text{MI}_L = \left( \text{EP}_L / \text{EP}_{5\text{F}} \right) \times 100\% \]  
(9)

Where \( L\{\text{LF, MF, HF}\} \).
4. GUI display for CHD monitoring

The four-channel signals are analyzed based on the proposed analysis method, and NHS and AHS samples are showed in Fig.6 and Fig.7. In order to detect cardiac sound simple and conveniently, feature parameters (mean±std) of NHS are chose as standard values, as shown in Table 2. As for murmur evaluation, if the MI values of detected signals are less than standard values (light color bar in Fig.6 and Fig.7), they are considered there may be no murmurs at these bands. However, if MI values are more than standard values (deep color bar in Fig.7), they are considered there exist murmurs at these bands.

This GUI monitoring system functions showed in Fig.8 and Fig.9, which include file reading, channel selection, multi-signals analysis and diagnosis report generation. Meantime, the multi-signals parameter information (HR, Fw, MI) from four positions (A, P, T and M) can be displayed timely, it is easy and convenient to understand and use. In Fig.8 and Fig.9, NHS and AHS clinical signals samples are showed, from the parameters, we can find much more useful information from the four positions. This health care in-home system is suitable for doctors and parents to monitor the CHD patient’s condition. It also can be used for healthy persons to monitor their cardiac sound condition daily at home.

5. Conclusion

The cardiac sound in-home measuring system for monitoring clinical heart disease is developed. Heart auscultation is a simple, non-invasive and cost-effective technique for clinical heart disease analysis. Furthermore, children’s cardiac auscultation is much more difficult because of their hyperactivity and other actions. The multichannel measuring system is composed of auscultation clothes and four electronic stethoscopes in order to obtain the multichannel cardiac signals efficiently. Further, the data analysis method was proposed to extract the diagnosis features, HR by CMW in time domain, Fw by AR-PSD in frequency domain.
and MI by WPE from energy analysis. The monitoring system based on GUI can implement functions for users to monitor the disease state of children in simple and convenient way. Finally, a case study on the normal and abnormal cardiac sounds is demonstrated to validate the usefulness and efficiency.

![Diagram](image1)

**Fig. 6.** NHS original multi-signals waveform (A, P, T and M), their AR-PSD curves and frequency widths (Fw), and the murmurs index (MI) at three bands (LF, MF and HF), white bars are standard values; light color bars means normal case.

**Fig. 7.** AHS original multi-signals waveform (A, P, T and M), their AR-PSD curves and frequency widths (Fw), and the murmurs index (MI) at three bands (LF, MF and HF), red bars means murmur, abnormal case.

![GUI](image2)

**Fig. 8.** GUI monitoring system of NHS case.

**Fig. 9.** GUI monitoring system of AHS (Tetralogy of Fallot) case.
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