Non-invasive diagnosis methods of coronary disease based on wavelet denoising and sound analyzing

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Abstract The heart sound is the characteristic signal of cardiovascular health status. The objective of this project is to explore the correlation between Wavelet Transform and noise performance of heart sound and the adaptability of classifying heart sound using bispectrum estimation. Since the wavelet has multi-scale and multi-resolution characteristics, in this paper, the heart sound signal with different frequency ranges is decomposed through wavelet and displayed on different scales of the resolving wavelet result. According to distribution features of frequency of heart sound signals, the interference components in heart sound signal can be eliminated by selecting reconstruction coefficients. Comparing de-noising effects of four wavelets which are haar, db6, sym8 and coif6, the db6 wavelet has achieved an optimal denoising effect to heart sound signals. The denoising result of contrasting different layers in the db6 wavelet shows that decomposing with five layers in db6 provide the optimal performance. In practice, the db6 wavelet also shows commendable denoising effects when applying to 51 clinical heart signals. Furthermore, through the clinic analyses of 29 normal signals from healthy people and 22 abnormal heart signals from coronary heart disease patients, this method can fairly distinguish abnormal signals from normal signals by applying bispectrum estimation to denoised signals via ARMA coefficients model.

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1. Introduction

Over the past 20 years, the morbidity and mortality of cardiovascular disease have increased constantly, and heart disease has been claimed as a pathema which imperils humankind’s health commonly and frequently (Wang et al., 2015; Zhou et al., 2015; An and Yu, 2016). The mechanical movements in the heart and the cardiovascular system can be reflected by heart sound, which contains the information about each part
of the heart and interactions among all different sections in heart in both physiological and pathological fields. The presences of noise and distortion in the heart sound have been classified as a useful and reliable information diagnosing heart and cardiovascular diseases in an early stage (Cheng et al., 2016; Zhou et al., 2005). Since the heart sound diagnosis has to be executed in the noiseless environment in order to acquire accurate heart sound signals, the heart sound detection system publicly adopts the analog method to eliminate noise utilizing the hardware, or the FIR digital filter (Wang et al., 2010; Joao et al., 2012; Gan et al., 2016; You et al., 2016). The weakness of heart sound signals, with the strength from 0.5 μV to 5 mV and the frequency from 1 to 1000 Hz, leads to vulnerability to external interferences, resulting in strong background noises in the signal detection process. Moreover, the traditional denoising method is not only undesirable in the elimination of noise, but also greatly impairs wanted signals in heart sound (Zhao et al., 2008; Zhu and Liu, 2006; Chen and Chen, 2005).

Comparing with the traditional method, the strategy presented in this paper has effectively denoised the heart sound signals through the Wavelet Transform. Besides, the wavelet filter used in this paper enables to control the cut-off frequency of the filter and reserve useful sections in signals whose frequency exceeds transmission bands according to the frequency distribution of heart sound: decomposing signals into detailed and approximate components on different ranges for the purpose of achieving effective separation between signals and noise (Zhang et al., 2013; Cheng and Li, 2015; Zhu, 2012; Yang et al., 2006; Liu, 2013).

The research of early diagnosis of coronary heart disease employs advanced digital signal processing technology to unveil the correlation between modern digital signal processing the heart sound and heart disease (Chen and Guo, 2006; Duan, 2016; Wang, 2014). In practice, heart sound diagnosis also has many advantages, such as, noninvasive operation, speediness, convenience, economy and so on.

2. Material and methods

The heart sound is an important biomedical signal of the human body, which contains a lot of information on heart health status. Analyzing the heart sound signal is quite essential to diagnose cardiovascular diseases, and its accuracy and reliability will directly affect the evaluation of patients’ clinical diagnosis and prognosis. Traditional heart sound recognition is less accurate because of the subjectivity and instability of auscultation which completes by doctors. Therefore, the research in non-invasive diagnosis methods based on modern information technology in the prevention and diagnosis of cardiovascular system diseases, like coronary heart disease, has become one of the most important issues in medical profession.

2.1. The compositions of heart sound signal

As other creatures in nature, the organs of human perform their physical activities in accordance with certain rules. The vibration caused by such physical activities will produce the sound signals, which contain the physiological and pathological characteristics. The heart sound signal is the weak signal, formed in the cardiac cycle, produced by the vibration of the myocardial contraction and relaxation, the opening and closing of the valve, and the impact of the blood stream on the heart wall and the aorta, which spread through the surrounding tissue to the chest wall.

The heart sound signal is a kind of biological weak signals under the strong noise background. It is easily affected by a number of human factors, for the reason that the heart sound signals is a kind of instable natural signals, which is signaled by the complex life. The changes of heart sound and the emergence of the heart murmur are the early symptoms of the organic pathological changes of heart. The change of physical structure of the heart directly leads to alteration in the heart sound signals, so the heart sound analyzing is a vital means in learning the status of the heart and large blood vessels. Each component of the heart sounds is shown in Fig. 1, including the first heart sound (s1), the second heart sound (s2), and under certain circumstances, there are the third heart sound (s3) and the forth heart sound (s4).

The first heart sound starts at 0.02–0.04 s after the beginning of the QRS wave on the electrocardiogram (ECG), accounting for 0.08–0.15 s, caused by blood flowing into the great vessels during ventricular contraction, mitral valve and tricuspid valve closure.

The occurrence of second heart sound (S2), starting from the tail of T wave on the electrocardiogram, is aroused by the blood flowing from the atrium into the ventricle when the aortic and pulmonary valves are closing but the atrioventricular valve is opening. The second heart sound occurs at the beginning of the diastolic period of the heart, at a relatively high frequency, which is usually shorter than the first heart sound, and takes about 0.07–0.12 s.

The third heart sound has low frequency and small amplitude, lagging 0.12–0.20 s behind the T wave on the electrocardiogram, accounting for 0.05–0.06 s, caused by rapid ventricular filling and ventricular wall vibration.

The fourth heart sound, with small amplitude, starts at 0.15–0.18 s of the P wave on the ECG, caused by Ventricular wall vibration when Atrial contraction and the blood flowing into the ventricle.

The diagnoses of coronary heart disease is divided into Invasive diagnosis Methods and Non-invasive diagnosis Methods. The Non-invasive diagnosis Method is generally based on electrical activity and pump activity of the heart, including electrocardiogram, dynamic electrocardiogram and phonocardiogram, echocardiography and modern medical imaging techniques such as NMR, CT, PET and so on. However, not all patients with coronary heart disease can be diagnosed by ECG and other methods. Some patients, with mild coronary heart disease, have normal ECG. So, using ECG is difficult to achieve accurate diagnosis of coronary heart disease.

Invasive diagnostic methods mainly refer to coronary angiography, which is currently the most reliable method of
diagnosing coronary heart disease. However, angiography is a traumatic diagnosis, with certain risks. In some cases, it may cause serious complications or even death. Accordingly, some patients are hesitant, and this treatment has not been accepted universally.

2.2. Diagnosis significance of heart sound

The systematic use of heart sounds to diagnose heart health began in 1817. For a long time, cardiac auscultation was one of the oldest methods of diagnosing cardiovascular diseases and understanding the function of the heart. Since the French doctor Laenec invented the stethoscope, medical personnel subjectively analyze and judge the heart sound obtained from stethoscope according to their knowledge and experience. Until now, this technique is still a basic method of diagnosing cardiovascular diseases, yet it has great limitations. And heart sound analysis can improve the accuracy of cardiovascular disease diagnosis. Non-invasive diagnosis method has great value and irreplaceable advantages in diagnosing cardiovascular diseases compared with what ECG and echocardiography do.

Domestic and foreign researchers use heart sound to analyze the coronary artery disease, beginning in the early 90s of the last century. It is generally believed that the heart sound is made up of the voice from the heart valve closure, myocardial stretch, the blood flowing and vocal tone.

Vascular stenosis caused by atherosclerosis can induce blood turbulence and vascular vibration. Heart sounds detected from the body surface can be used to diagnose diseases brought by blood clogging. Although the heart sound is quite weak and the cardiac murmur is relatively prominent, signals can still be detected because of the minimum pressure on the coronary artery and the maximum blood flowing in the coronary artery. Besides, clinical practices have proved this theory.

Based on the theoretical modeling, simulation and clinical experiment, the research on the diagnosis method of heart sound is carried out for a long time. Cheng To, John R. Burg and Kathlean A. Weaver use selective coronary angiography to demonstrate that diastolic murmurs are associated with coronary clogging. Besides, the aortic diastolic murmur in patients of coronary heart disease has disappeared after coronary artery bypass surgery. Consequently, they put forward the idea and method of using heart sound to diagnose coronary artery disease. L Semmlow and W. Welkowitz in 1983 used Fourier transform researching in the difference of Heart sound spectrum during the period of relaxation between patients with coronary heart disease and normal subjects. They also found that the high-frequency energy increased in patients with coronary heart disease.

M. Akay’s study is the most representative one in heart sound. Their research results reveal that the over flow happens when the blocking rate of coronary artery stenosis between 25% and 95% and this flow generates a faint heart signal with high frequency, which indicated the blocking in tubular artery. In 1992, M. Akay uses adaptive filtering method to eliminate the background noise of the heart sound signal. The ARMA model and AR model were established for the diastolic heart sound signal. Using the power spectra and poles model as diagnostic parameters has created many valuable results. Experiments show the relation between the high frequency of heart sounds and coronary artery indeed existed.

2.3. Digital filtering of heart sound signal

The heart sound signal is a kind of biological weak signals under the strong noise background, and is easily disturbed by noises in detection processes. The collection of heart sound is mixed with manifold noise signals, such as environmental noise, power frequency noise, EMG noise, acquisition equipment noise and skin fricative noise. Therefore, only relying on the hardware filtering in heart sound acquisition system cannot complete the elimination of interference in the signal, and digital filtering is also needed to filter out a variety of noises in heart sound signals as far as possible.

In recent years, Wavelet Transform which is studied and valued by many scholars both at home and abroad, has been widely used in many fields including biomedical signal denoising, speech signal processing and related signal processing because of its excellent denoising characteristics.

The Wavelet Transform not only inherits the characteristics of the Fourier transform, but also makes up many deficiencies of Fourier analysis. Therefore, it has made a rapid progress and been used widely.

The translation and contraction of Wavelet basis allows a flexible time-frequency window, which becomes narrow at high frequency and wide at low frequency. It is well suited for analyzing non-stationary heart sound signals, as it can focus on any details of the analyzed object.

At present, Wavelet Transform has been successfully applied in the fields of Biomedical Engineering, Intelligent Signal Processing, Image Processing, Speech and Image Coding, Speech Recognition and Synthesis, Multi-scale Edge Extraction and Reconstruction, Fractal and Digital Television.

Wavelet Transform can be described as follows:

\[
\begin{align*}
WTf(a,b) &= \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} f(x) \psi^a \left( \frac{x-b}{a} \right) dx \\
\psi_{a,b}(x) &= \frac{1}{\sqrt{|a|}} \psi \left( \frac{x-b}{a} \right) \quad a, b \in R, a \neq 0
\end{align*}
\]

(1)

where \( \psi_{a,b}(x) \) represents Wavelet generating function, a represents scaling factor, b represents the time-shifting factor, when \( b \) take different values, the wavelet along the timeline move to a different location, \( \psi^* (t) \) represents complex conjugation of \( \psi (t) \).

In order to facilitate the use of computer processing, it is necessary to perform the discrete processing on the above-described transformation. Let’s start from the wavelet generating function:

\[
2^k \psi (2^k x - k)
\]

(2)

Namely:

\[
\begin{align*}
a &= \frac{1}{2^k} \\
b &= \frac{k}{2^k}
\end{align*}
\]

(3)

It is called dyadic wavelet. Discrete Binary Wavelet Decomposition Algorithm is shown in Fig. 2:

Discrete dyadic Wavelet Transform and reconstruction can be realized by Mallat algorithm (Gan et al., 2016), therefore, the decomposition algorithm of the Wavelet Transform can be described as follows:
The collection of the sample signal was completed in the First Affiliated Hospital of Hunan University of Traditional Chinese Medicine and the Air Force General Hospital. The samples were divided into two groups, coronary heart disease...
Fig. 4  (a) Heart sound signal of un-filtered. (b) Filtered heart sound signal by db6.
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and non-coronary heart disease. Each group had 18 patients. The coronary-group was confirmed by the coronary angiography.

The ARMA model order number P and Q in the bispectrum estimation are important for the classification of heart sounds. By selecting different parameters of P and Q in MATLAB, the calculation is carried out. When \( p = 2, q = 1 \), the bispectrum of normal and abnormal heart sounds are shown in Fig. 5. Fig. 5(a) shows a normal heart sound signal of the double spectrum, while Fig. 5(b) is a case of

\[ (a) p=2, q=1 \text{ the Bispectrum of normal heart sound signals} \]

\[ (b) p=2, q=1 \text{ the Bispectrum of abnormal heart sound signals} \]
abnormal heart sound signal. As illustrated in Fig. (a) and (b), the upper-left one is the bispectrum of the armarts function estimation, and the lower-left is the bispectrum of the armaqs function. The lower right is the armaqs function estimation, and the lower-right is the armaqs function estimation of the bispectrum three-dimensional map.

Fig. 6  (a) $p=3$, $q=2$ the Bispectrum of normal heart sound signals. (b) $p=3$, $q=2$ the Bispectrum of abnormal heart sound signals.
When \( p = 3 \) and \( q = 2 \), the bispectra of the normal and abnormal heart sounds are shown in Fig. 6(a) and (b), respectively.

When \( p = 4 \) and \( q = 3 \), the bispectra of the normal heart sound signal and the abnormal heart sound signal are shown in Fig. 7(a) and (b), respectively.

When \( p = 5 \) and \( q = 4 \), the bispectra of the normal heart sound signal and the abnormal heart sound signal are shown in Fig. 8(a) and (b), respectively.

When \( p = 6 \) and \( q = 5 \), the bispectra of the normal heart sound signal and the abnormal heart sound signal are shown in Fig. 9(a) and (b), respectively.
(a) $p=5$, $q=4$ the Bispectrum of normal heart sound signals.

(b) $p=5$, $q=4$ the bispectrum of abnormal heart sound signals.

Fig. 8  (a) $p = 5, q = 4$ the Bispectrum of normal heart sound signals. (b) $p = 5, q = 4$ the bispectrum of abnormal heart sound signals.
In addition to $p=2$, $q=1$, the abnormal heart sound signal has a higher frequency component than the normal heart sound signal in the bispectrum, so we can distinguish the normal heart sound signal of healthy people and the abnormal one of patients basing on the bispectrum, and Non-invasive diagnosis can be achieved.

4. Conclusion

The heart sound signal is a kind of unstable nature signal emitted from complex beings and also representative biological signal of human, yet that signal could be disturbed and influenced by human factors easily, because of its characters of weakness,
strong noise interference and randomness. In order to acquire accurate heart sound signals, filtering interference noises is the foundation and prerequisite of Non-invasive diagnosis of coronary heart disease. In this paper, decomposing five layers of the heart sound by db6 wavelet can filter various random noises, in the detection processing, effectively. Finally, the 29 cases normal signals from healthy people and 22 cases abnormal heart signals from coronary heart disease patients are accurately distinguished, through selecting the appropriate ARMA model parameters of the 51 filtered heart sound signals to conduct bispectrum estimation.

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