IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 24, 2020, accepted August 29, 2020, date of publication September 3, 2020, date of current version September 15, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3021093

Discrimination of the Diastolic Murmurs in Coronary Heart Disease and in Valvular Disease

HAIXIA LI [1], GUOFENG REN [1], XIAOPU YU [2], DONGYING WANG [2], AND SHIZHE WU [3]

[1] Department of Electronics, Xinzhou Teachers University, Xinzhou 034000, China
[2] Shanxi Medical University of China, Taiyuan 035100, China
[3] Taiyuan Zhida Ivy League Middle School, Taiyuan 030006, China

Corresponding author: Haixia Li (55047866@qq.com)

This work was supported in part by the Science and Technology Innovation Project of Universities in Shanxi Province under Grant J2020544, in part by the Shanxi Province Key Research and Development Plan under Grant 201803D121089, in part by the Innovation Special Zone Program under Grant 18-H863-05-ZT-001-018-03, in part by the Fund for Shanxi ''1311 Project'' Key Subject Construction under Grant 2016M600243, in part by the Research on Blended Teaching Method of Signal Processing Courses for Application-oriented Talents Training under Grant J2019174, and in part by the Ethics Committee of the Second Affiliated Hospital of Shanxi Medical University of China under Grant EC2019053008.

ABSTRACT Previous studies have shown that the acoustic characteristics of coronary heart disease (CHD) are the diastolic turbulent murmurs. But there is little research on how to distinguish the differences between diastolic turbulent murmurs and diastolic valvular murmurs. In order to improve the diagnosis accuracy of CHD based on the analysis of diastolic murmurs, empirical wavelet transform was applied to distinguish the difference of diastolic murmurs between in CHD and in valvular disease. Firstly, the spectrum of diastolic heart sounds was divided into three modes and the segmentation boundaries were set as [150, 200] Hz. Next, the diastolic modal spectrums were obtained. It is found that the essential difference of diastolic murmurs between in CHD and in mitral stenosis is the third modal spectrum. Finally, the characteristic parameter P3 was defined and used to distinguish the diastolic murmurs in CHD and in valvular disease. The performance of the proposed method is tested and the results show when the proposed method was used to identify the diastolic murmurs of CHD, Se is 94.7%, Pp is 93.4% and Oa is 88.7%; When the proposed method identifying the diastolic murmurs of valvular disease, Se is 93.3%, Pp is 94.6% and Oa is 88.6%.

INDEX TERMS Diastolic murmurs, coronary heart disease (CHD), valvular disease, empirical wavelet transform (EWT).

I. INTRODUCTION

Coronary heart disease (CHD) has become the ''number one killer'' of human beings, while most of its detection methods are invasive, expensive or unable to achieve early diagnosis [1], [2]. Early coronary blocking will not cause abnormal changes in ECG, only when the coronary blocking rate is over 70% ∼ 75% can the ECG signal be changed [3]. Using the reflection principle of ultrasonic wave to detect the degree of coronary artery blockage is the principle of B-ultrasonography. But when the external environment changes or the intensity of ultrasound in the body and the emission path change, there will be false emission, which can result in the decrease of CHD's diagnostic accuracy [4]. Nuclear magnetic resonance, CT, PET are expensive, poor CHD people can not easily beat the cost [5], [2]. Coronary angiography is currently the ''gold standard'' for the diagnosis of CHD. However, angiography is an invasive diagnosis with certain risks. In some cases, it can lead to serious complications and even death [6].

Changes in heart sounds and the appearance of murmurs are often the earliest features of organic heart disease [3]. With the development of electronic stethoscope and digital signal processing technology, many scholars have devoted themselves to the study of the acoustic characteristics of heart sounds of CHD, hoping to solve the problem of early accurate diagnosis of CHD [7], [8]. Many Previous studies have proved that the acoustic characteristics of CHD are the diastolic turbulent murmurs [9]–[13]. Sangster and Oakley have studied the phonocardiograms (PCG) of patients with CHD and confirmed the application value of diastolic murmurs in the diagnosis of CHD [14]. J. L. Semmlow and

The associate editor coordinating the review of this manuscript and approving it for publication was Filbert Juwono.

W.Welkowitz et al used Fourier transform to study the differences of diastolic heart sound spectrum between patients with CHD and normal people, and found that high-frequency energy spectrum of the diastolic heart sound increased in patients with CHD [15]. Metin Akay and JL Semmlow *et al.* used the eigenvector method to study the diastolic heart sound of coronary artery stenosis before and after angioplasty and showed that the diastolic murmurs were equivalent to a narrowband signal with high frequency, which were associated with coronary artery stenosis [16]. Zhao applied EMD (empirical mode decomposition) algorithm and Hilbert transformation to analyze the diastolic heart sound of CHD and found that the average instantaneous frequency of diastolic heart sounds in patients with CHD is higher than that of normal people [17].

However, high frequency diastolic murmurs are known to occur not only in CHD, but also in valvular diseases, such as mitral stenosis, tricuspid stenosis, and aortic and pulmonary valve regurgitation. Up to now, there is little study focus on how to distinguish the differences of diastolic murmurs in CHD and in valvular diseases. Although there are many clinical methods to separate CHD from valvular diseases, such as CT, echocardiography, ECG, X-ray, etc. But as mentioned above, these methods have some drawbacks in solving the early non-destructive diagnosis of CHD. In order to use diastolic murmurs to solve the early non-invasive detection of CHD, the interference of diastolic murmurs caused by valvular disease should be eliminated firstly.

In addition, the friction peak noise caused by the friction between the hand-held stethoscope and the skin seriously interferes with the weak diastolic turbulent murmur. Therefore, the accuracy and specificity of diagnosing CHD based on diastolic turbulent murmurs need to be further improved.

In this paper, a MEMS (micro-electro-mechanical systems) electronic stethoscope with high signal-to-noise ratio (SNR) is used to collect heart sound signal of the patients with CHD which can reduce the difficulty of removing noise while retaining weak pathological information of heart sounds. It is proposed that using empirical wavelet transform (EWT) to study the differences of diastolic murmurs between in CHD and in valvular disease. The heart sound signal of valvular disease is collected from Michigan heart sound Database.

II. PROPOSED METHOD

The proposed method for distinguishing the diastolic murmurs in CHD and in valvular disease includes several steps: preprocessing (resampling, normalization, denoising, segmentation), decomposition of diastolic heart sound using EWT, feature extraction, classification. Figure 1 illustrates a simplified block diagram of the proposed method for discrimination the diastolic murmurs in CHD and in valvular disease.

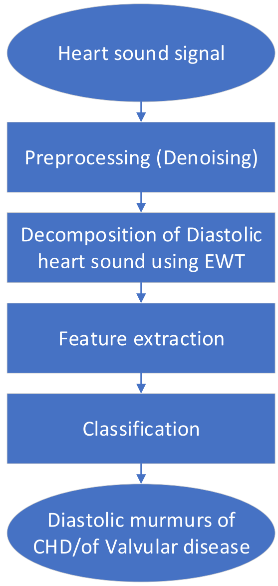


FIGURE 1. Diagram of the proposed method for the discrimination of diastolic murmurs in CHD and in Valvular disease.

A. WAVELET THRESHOLD DENOISING

The biggest problem encountered in the analysis of heart sound signal of CHD is environmental noise. This problem is generally solved from two aspects, one is to develop more advanced electronic stethoscope, the other is to find more advanced signal de-noising algorithm. The advanced equipment can collect the signal with high SNR (such as the MEMS electronic stethoscope), thus greatly reducing the difficulty of signal de-noising algorithm.

In this paper, the heart sound sensor of the MEMS stethoscope was designed with the aid of the hydrophone which imitated the fish lateral line structure [18]. Because a kind of medical coupling solvent whose density is approximate to the human's blood was used to encapsulate the heart sound sensor, the attenuation of the heart sound signal passing to the sensor's micro-structure via human tissue reduced greatly. In addition, when using the MEMS electronic stethoscope to collect heart sound signal, there is no need to hold it all the time. The stethoscope was just placed on the left border of patient's chest. Therefore, its sensitivity and SNR has been further improved and its SNR is higher than 3M Littmann 3200 stethoscope 8.2 db. Literature [18] have presented the design and manufacturing process of the MEMS electronic stethoscope in detail. Heart sound data with high SNR can greatly reduce the difficulty of data processing and improve the accuracy of data analysis results.

The noise type of coronary heart sound data collected by MEMS electronic stethoscope is simple, and the wavelet threshold denoising algorithm was used to denoise coronary heart sound data. Sym3 wavelet basis and three-layer decomposition can be uniformly adopted. The threshold function is uniformly set as (1) [19]:

$$\beta_j = \sigma_j^{Noise}\sqrt{2\log(N_j)} \tag{1}$$

N_j is the length of the signal at the decomposition scale j. σ_j^{Noise} is the noise variance, it can be calculated through formula (2):

$$\sigma_j^{Noise} = \frac{median(|CD_j|)}{0.6745} \tag{2}$$

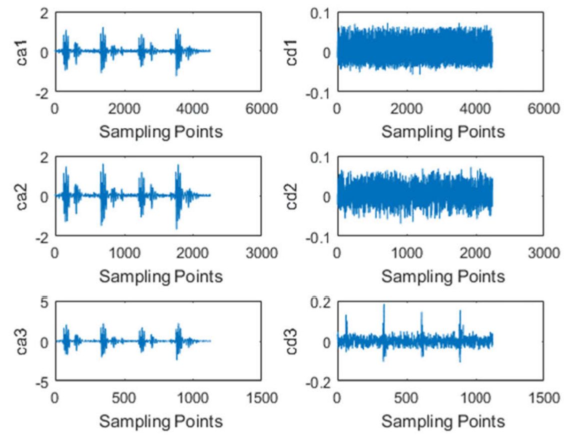


FIGURE 2. Sym3 wavelet three-layer decomposition of CHD's heart sounds.

For example, a noise coronary heart sound data was collected by MEMS electronic stethoscope. The patient, a 59-year-old man, underwent coronary angiography and was determined to have 40% midstream stenosis of the anterior descending branch. The recording duration of this heart sound is 15 second. Three complete cardiac cycles were selected.

The detailed components and approximate components of each layer were obtained after the Sym3 wavelet was used to decompose the noised coronary heart sound signal into three layers, as shown in Figure 2. It can be seen the noise is simple and is mainly distributed in the detail component of each layer. After the third layer, the noise coefficient become very smaller.

The comparison waveforms before and after noise elimination of CHD's heart sound data are shown in Figure 3. It can be found that the noise elimination effect is relatively ideal. While removing the noise, weak pathological information- the third and the fourth heart sound signal- is retained.

B. DECOMPOSITION OF DIASTOLIC HEART SOUND USING EWT

According to the previous studies, most of the diastolic murmurs in valvular heart disease were within 200Hz, while the diastolic turbulent murmurs in CHD were above 200Hz [15]. In order to further improve the specificity and accuracy of the algorithm in diagnosing CHD based on diastolic murmurs, it is needed to study the characteristic parameters to distinguish the diastolic murmurs in CHD and in valvular disease.

EWT combines the advantages of wavelet transform and empirical mode decomposition (EMD) and can also overcome the disadvantages of EMD producing false modes [20]. Because of the advantages of EWT algorithm, in recent years, it has been widely used in various engineering applications, such as harmonic detection of power system, classification of heart sound murmurs [21], feature extraction for first heart sound [22], etc. It decomposes signal through dividing the signal's spectrum flexibly and constructing Meyer wavelet filter banks according to the segmentation boundaries.

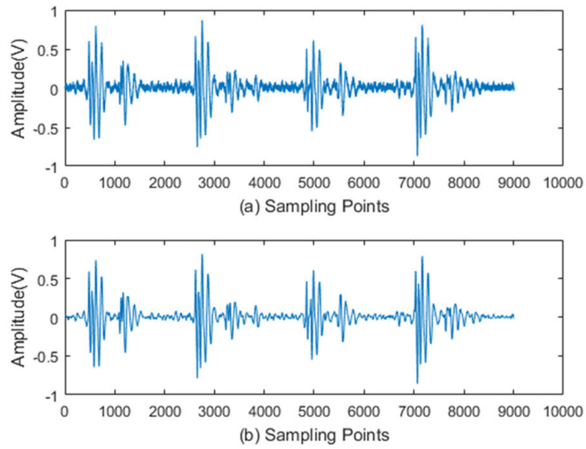


FIGURE 3. CHD heart sound before and after threshold denoising. (a) The waveform of CHD's heart sound before denoising;(b) The waveform of CHD's heart sound after denoising.

Therefore, EWT is proposed to decompose the diastolic heart sound of CHD and valvular disease. The support of the filter depends on the spectral information of the signal to be analyzed. The signal spectrum is normalized to $[0, \pi]$. If the signal is composed of N single-frequency components, the Fourier spectrum of the signal need to be divided into N intervals, and then N bandpass filters are constructed. In addition to the boundary points 0 and π, we need to identify N-1 more points of the spectrum. Signal's Fourier spectrum segmentation interval can be expressed as: $[w_{n-1}, w_n]$ $(n = 1, 2\ldots, N)$. The amplitude is dimensionless, and the segmentation of Fourier spectrum based on EWT is shown in Figure.4. w_n is in the center of one support of bandpass filter. The width of support is $2\tau_n$, which is the transition area between every filter. In Figure 4, the shaded part is the filter support. Each spectrum interval can be signed Λ_n and should satisfy the formula (3):

$$U_{n=1}^{N}\Lambda_n = [0,\pi] \tag{3}$$

Empirical wavelet transform is constructed on each spectrum segmentation, namely a series of Meyer's wavelet filter Banks.

The scale function and empirical wavelet function of EWT can be expressed by equations (4) and (5).

$$\hat{\phi}_n(w) = \begin{cases} 1, & if\ |w| \le w_n - \tau_n \\ \cos\left[\frac{\pi}{2}\beta\left(\frac{1}{2\tau_n}(|w| - w_n + \tau_n)\right)\right], & \\ \quad if\ w_n - \tau_n \le w_n + \tau_n & \\ 0, & otherwise \end{cases} \tag{4}$$

$$\hat{\psi}_n(w) = \begin{cases} 1, & if\ w_n + \tau_n \le |w|\, w_{n+1} - \tau_{n+1} \\ \cos\left[\frac{\pi}{2}\beta\left(\frac{1}{2\tau_{n+1}}(|w| - w_{n+1} + \tau_{n+1})\right)\right], & \\ \quad if\ w_{n+1} - \tau_{n+1} \le |w| \le w_{n+1} + \tau_{n+1} & \\ \quad \sin\left[\frac{\pi}{2}\beta\left(\frac{1}{2\tau_n}(|w| - w_n + \tau_n)\right)\right] & \\ \quad if\ w_n - \tau_n \le |w| \le w_n + \tau_n & \\ 0, & otherwise \end{cases} \tag{5}$$

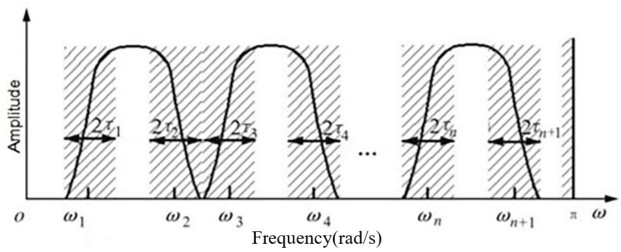


FIGURE 4. Segmentation of the Fourier spectrum.

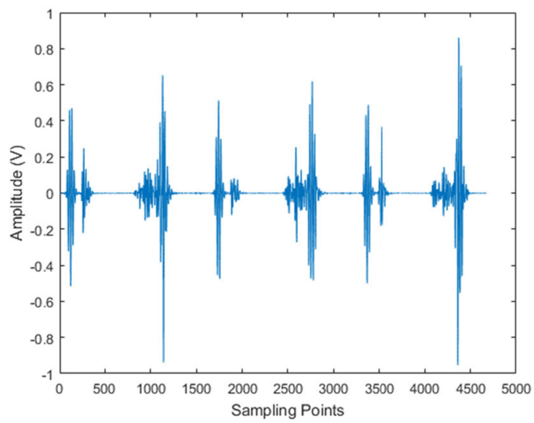


FIGURE 5. Heart sound data of mitral stenosis with early and late diastolic murmurs.

where, $\beta(x)$ is a function that satisfy equation (6):

$$\beta(x)=\begin{cases}0, & if\ x\le 0\\ and\,\beta(x)+\beta(1-x)=1\forall x\in[0,1] & \\ 1, & if\ x\ge 1\end{cases}\tag{6}$$

In fact, many functions can satisfy equation (6), but $\beta(x)$ described in equation (7) is most frequently used in reference [17]:

$$\beta(x)=x^4(35-84x+70x^2-20x^3)\tag{7}$$

After the heart sound signal was preprocessed, diastolic heart sound signal was extracted for further analysis. EWT was used to divide the signal's spectrum. The boundaries for segmentation of the spectrum was set as [150, 200] Hz. Then the diastolic heart sound signal was decomposed into three modes: 0∼150 Hz, 150∼200Hz, >200Hz. Finally, the spectrums of the three modal signals were obtained respectively and the significant difference of diastolic murmurs in CHD and in valvular disease is the third modal spectrum.

C. FEATURE EXTRCTION

In order to further demonstrate the algorithm flow and feature comparison, the heart sound data of one patient with mitral stenosis and one with CHD were used to illustrate.

Firstly, a heart sound data of mitral stenosis with early and late diastolic murmurs was selected from Michigan heart sound Database for study. The recording duration of the heart sound data is one minute and one second. A part of the waveform of this heart sound data is displayed in Figure 5. Its diastolic heart sound signal (from the end of S2 to the start of next S1) was selected as shown in Fig.6(a). Its spectrum was shown in Fig.6(b). The spectrum was divided into three parts:0∼150Hz, 150∼200Hz and >200Hz as shown in Fig.6(c).

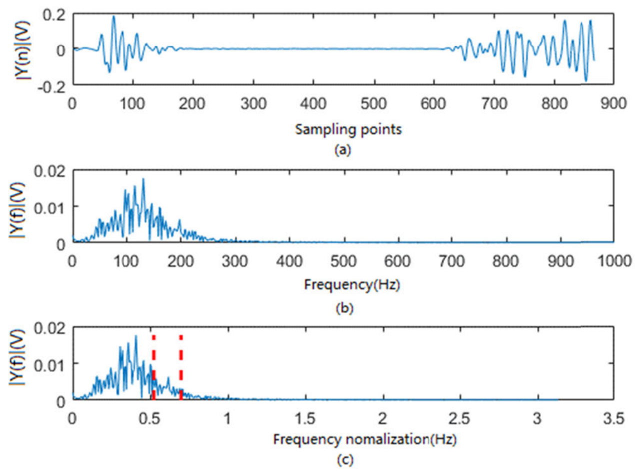


FIGURE 6. The spectrum segmentation of diastolic heart sound with mitral stenosis. (a) Waveform of diastolic heart sound; (b) The spectrum of diastolic heart sound; (c) The spectrum segmentation using by EWT.

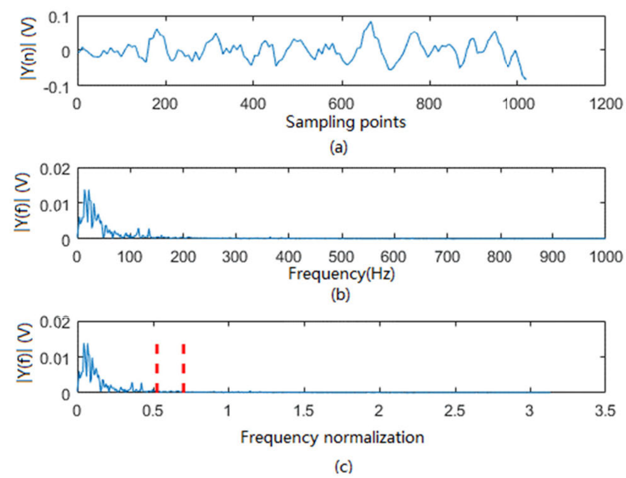


FIGURE 7. The spectrum segmentation of diastolic heart sound with CHD. (a) Waveform of diastolic heart sound; (b) The spectrum of diastolic heart sound. (c) The spectrum segmentation using by EWT.

Next, the same algorithm was used to analyze the diastolic heart sounds of CHD. The heart sound signal of the patient with CHD here is the same as that shown in Figure 3.

The waveform of diastolic heart sound of CHD was selected as shown in Fig.7(a). The spectrum and its segmentation using EWT was shown in Fig.7(b) and Fig.7(c).

According to the segmentation of spectrum, the Meyer wavelet filter banks are constructed. The diastolic heart sound signal is decomposed into three different modes as shown in Figure 8.

The three diastolic modal time-domain signals obtained by the mode decomposition were Fourier transformed to get their spectrums. Then the differences of the three modal

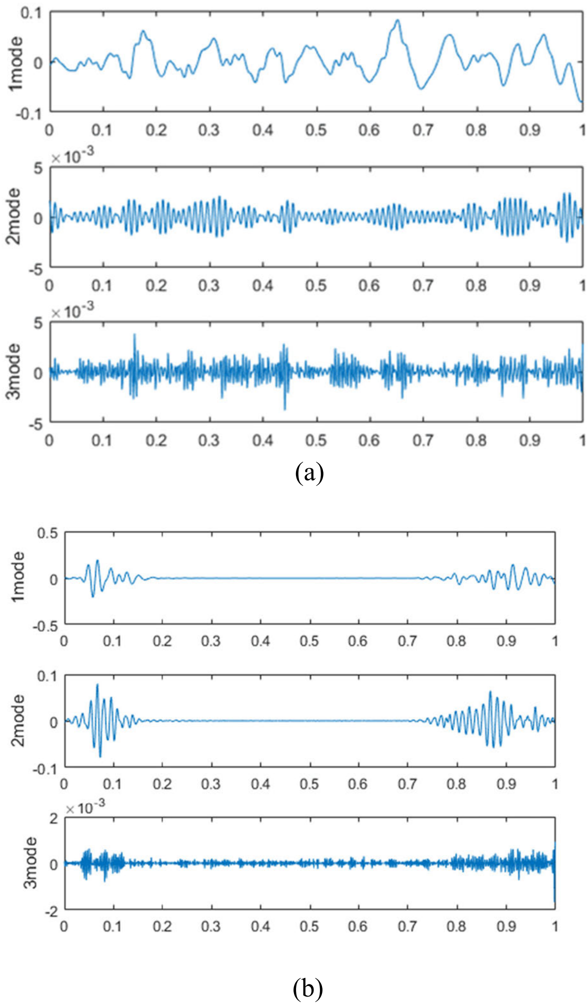


FIGURE 8. Comparison of diastolic modal decomposition between CHD and mitral stenosis. (a) diastolic modal decomposition of CHD; (b) diastolic modal decomposition of mitral stenosis.

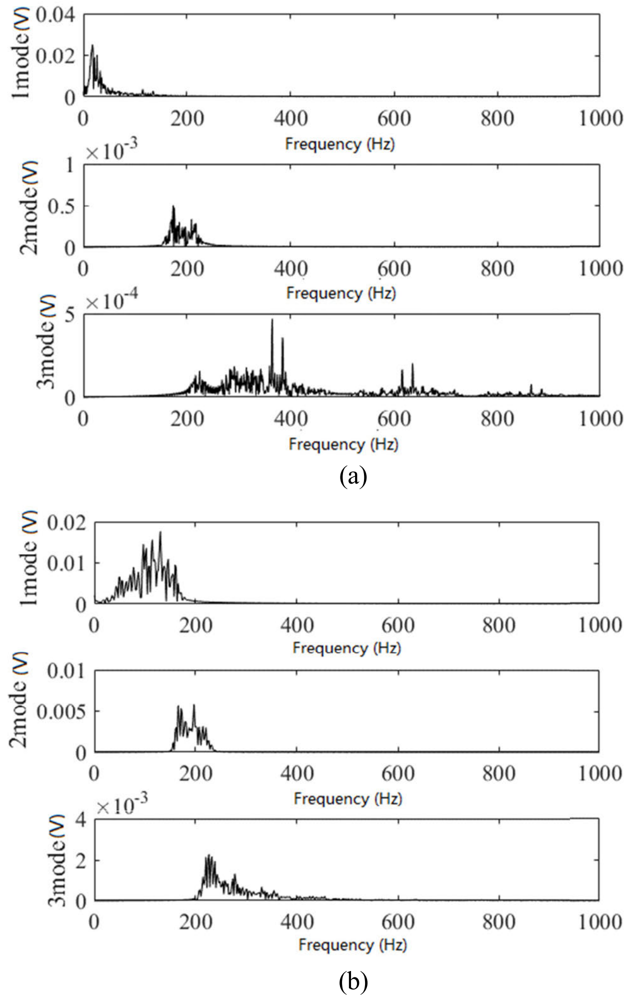


FIGURE 9. Comparison of diastolic modal spectrum between CHD and mitral stenosis. (a) three diastolic modal spectrums of CHD; (b) three diastolic modal spectrums of mitral stenosis.

spectrums in both CHD and in mitral stenosis can be clearly seen in Figure 9.

It is found that the essential difference of diastolic murmurs in CHD and in mitral stenosis is their third modal spectrum as shown in Figure 9. The third diastolic modal spectrum of CHD has more energy concentrated in 300∼400Hz. While the third diastolic modal spectrum in mitral stenosis has more energy below 250Hz.

Therefore, the ratio of spectral energy greater than 250Hz and spectral energy less than 250Hz in the third diastolic modal spectrum can be used as the feature to directly distinguish diastolic murmurs in CHD and in valvular disease. The ratio was named as P3 in this paper and it can be expressed by the equation (8).

$$P_3 = \frac{E(3)_{f \geq 250Hz}}{E(3)_{f < 250Hz}} \tag{8}$$

III. CLASSIFICATION RESULTS

To further verify whether P3 could be used to distinguish diastolic murmurs in all CHD and in all valvular disease, experiments were carried out to calculate P3 of all kinds of CHD and valvular disease using the same algorithm proposed before. And their results can be seen in Table 1. MEMS electronic stethoscope was used to collect 30 CHD heart sounds, and 3M electronic stethoscope was used to collect the 20 CHD heart sound. Ten diastolic periods were analyzed for each CHD heart sound data. There are 20 diastolic heart sounds of CHD from Michgan heart sound Database. Valvular disease includes mitral stenosis, tricuspid stenosis, aortic and pulmonary valve regurgitation *et al.* Valvular diastolic murmurs also include early diastolic murmur, late diastolic murmur, mid-diastolic murmurs, and full diastolic murmurs. The mean value of P3 was calculated and the statistical results were shown in Table 1.

According to the statistical results in Table 1, P3, which is used to distinguish diastolic murmurs caused by CHD or by valvular disease, can be chosen as 8. That means if P3 is greater than 8, the diastolic murmurs are caused by CHD. If P3 is less than 8, the diastolic murmurs are caused by valvular disease. Finally, 150 diastolic signals of CHD and valvular disease were collected, and the classification rule was used to calculate the accuracy and specificity of the

TABLE 1. Comparison of P3 between CHD and valvular heart disease.

Type of diastolic heart sounds	Source	Number of Recordings	Every Recoding's duration	Average value of P3
CHD	MEMS electronic stethoscope	30	10 cardiac cycles	21.8
	3M Littaman	20	10 cardiac cycles	12.3
	Michgan Database	2	10 cardiac cycles	40.25
Valvular disease	MEMS electronic stethoscope	6	10 cardiac cycles	0.67
	3M Littaman	6	10 cardiac cycles	6.3
	Michgan Database	3	10 cardiac cycles	0.76

TABLE 2. Performance of the proposed method for discrimination of diastolic murmurs in CHD and in valvular disease.

Different Methods	Type of Diastolic Murmurs	Total Cardiac Cyles	TP	FN	FP	Se(%)	Pp(%)	Oa(%)
HHT	In CHD	150	82	68	84	54.7	49.4	35.0
	In Valvular Disease	150	66	84	68	44	49.2	30.2
Proposed Method	In CHD	150	142	8	10	94.7	93.4	88.7
	In Valvular Disease	150	140	10	8	93.3	94.6	88.6

proposed algorithm as shown in Table 2. So far, no studies have been reported to distinguish the diastolic murmurs in CHD and in valvular disease. In order to demonstrate the effectiveness of the proposed method in distinguishing the diastolic murmurs in CHD and in valvular disease, comparison experiment was carried out. The method proposed by Zhao in reference [17] was used to compare with the proposed method in this paper. Zhao used HHT (Hilbert Huang Transform) to get the diastolic marginal spectrum of diastolic heart sounds. Then parameter P was used to distinguish CHD and non-CHD. Here, P can also be used to distinguish diastolic murmurs in CHD and in valvular disease. P is the marginal spectral energy ratio and was defined as equation (9):

$$P = \frac{E_{f \geq 200Hz}}{E_{F<200Hz}} \tag{9}$$

The comparison results show that the proposed algorithm has great advantages over HHT algorithm in distinguishing the diastolic murmur in CHD and in valvular disease as shown in Table 2.

IV. CONCLUSION

This work applied EWT algorithm in distinguishing diastolic murmurs between in CHD and in valvular diseases. The entire diastolic period (from the end of S2 to the end of the next S1) was selected as the key analysis period. The diastolic spectrum segmentation boundary was set as [150, 200] Hz. Then diastolic signal was decomposed into 3 modes, corresponding to 0∼150Hz, 150∼200Hz, and >200Hz respectively. Every mode's spectrum was obtained and it is found that the essential difference of diastolic murmurs in CHD and in valvular disease is the third mode's spectrum. The third mode's spectrum show the diastolic murmurs of CHD usually concentrated in 300∼400Hz while the diastolic murmurs of valvular disease were always below 250Hz. Therefore, P3, the ratio of energy greater than 250Hz to energy less than 250Hz in the third mode spectrum, was used to distinguish diastolic murmurs between in CHD and in valvular disease.

After a large number of experiments, the statistical results in Table 1 show that P3 can differentiate diastolic murmurs in CHD and in valvular disease very well. The statistical results in Table 2 further showed the performance of the proposed method in distinguishing the diastolic murmur in CHD and in valvular disease is superior to HHT. When the proposed method identifying the diastolic murmurs of CHD, the sensitivity(Se) is 94.7%, specificity(Pp) is 93.4% and accuracy (Oa) is 88.7%; When the proposed method identifying the diastolic murmurs of valvular disease, the sensitivity(Se) is 93.3%, specificity(Pp) is 94.6% and accuracy (Oa) is 88.6%.

With the further accumulation of heart sound data, intelligent algorithms such as support vector machine can be used to find P3, a characteristic parameter used to distinguish diastolic murmurs in CHD and in valvular disease, and the performance of the proposed method may be improved.

ACKNOWLEDGMENT

This study was approved by the ethics committee of The Second Affiliated Hospital of Shanxi Medical University of China (EC2019053008).

Availability of data and materials online: https://download.csdn.net/download/ximifly/1599669; http://www.med.umich.edu/lrc/psb_open/html/repo/primer_heartsound/primer_heartsound.html.

REFERENCES

[1] A. Elbadawi, B. Baig, I. Y. Elgendy, E. Alotaki, A. H. Mohamed, K. Barssoum, D. Fries, M. Khan, and R. N. Khouzam, "Single coronary artery anomaly: A case report and review of literature," *Cardiol. Therapy*, vol. 7, no. 1, pp. 119–123, Jun. 2018.

[2] D. Andreini, S. Mushtaq, G. Pontone, E. Conte, M. Guglielmo, A. Annoni, A. Baggiano, A. Formenti, V. Ditali, M. E. Mancini, S. Zanchi, E. Melotti, D. Trabattoni, P. Montorsi, P. M. Ravagnani, C. Fiorentini, A. L. Bartorelli, and M. Pepi, ''Diagnostic performance of coronary CT angiography carried out with a novel whole-heart coverage high-definition CT scanner in patients with high heart rate,'' *Int. J. Cardiol.*, vol. 257, pp. 325–331, Apr. 2018.

[3] Y. M. Akay, M. Akay, W. Welkowitz, J. L. Semmlow, and J. B. Kostis, ''Noninvasive acoustical detection of coronary artery disease: A comparative study of signal processing methods,'' *IEEE Trans. bio-medical Eng.*, vol. 40, no. 6, pp. 571–578, 1993, Jun. 1993.

[4] B. K. Courtney, A. L. Robertson, A. Maehara, J. Luna, K. Kitamura, Y. Morino, R. Achalu, S. Kirti, P. G. Yock, and P. J. Fitzgerald, ''Effects of transducer position on backscattered intensity in coronary arteries,'' *Ultrasound Med. Biol.*, vol. 28, no. 1, pp. 81–91, Jan. 2002.

[5] W. Zhaohui, ''The role of cardiac magnetic resonance (CMR) in the diagnosis of cardiomyopathy: A systematic review,'' *Malawi Med. J.*, vol. 31, no. 3, pp. 240–244, Sep. 2019.

[6] J. L. Semmlow, ''Improved heart sound detection and signal-to-noise estimation using a low-mass sensor,'' *IEEE Trans. Biomed. Eng.*, vol. 63, no. 3, pp. 647–652, Mar. 2016.

[7] A. Dragomir, A. Post, Y. Akay, H. Jneid, D. Paniagua, A. Denktas, B. Bozkurt, and M. Akay, ''Acoustic detection of coronary occlusions before and after stent placement using an electronic stethoscope,'' *Entropy*, vol. 18, no. 8, p. 281, Jul. 2016.

[8] A. N. Makaryus, J. N. Makaryus, A. Figgatt, D. Mulholland, H. Kushner, J. L. Semmlow, J. Mieres, and A. J. Taylor, ''Utility of an advanced digital electronic stethoscope in the diagnosis of coronary artery disease compared with coronary computed tomographic angiography,'' *Amer. J. Cardiol.*, vol. 111, no. 6, pp. 786–792, Mar. 2013.

[9] J. R. Burg, K. A. Weaver, T. Russell, and D. G. Kassebaum, ''Disappearance of coronary artery stenosis murmur after aortocoronary bypass,'' *Chest*, vol. 63, no. 3, pp. 440–442, 1973.

[10] W. Dock and S. Zoneraich, ''A diastolic murmur arising in a stenosed coronary artery,'' *Amer. J. Med.*, vol. 42, no. 4, pp. 617–619, 1967.

[11] S. E. Schmidt, C. Holst-Hansen, J. Hansen, E. Toft, and J. J. Struijk, ''Acoustic features for the identification of coronary artery disease,'' *IEEE Trans. Biomed. Eng.*, vol. 62, no. 11, pp. 2611–2619, Nov. 2015.

[12] S. Winther, L. Nissen, S. E. Schmidt, J. S. Westra, L. D. Rasmussen, L. L. Knudsen, L. H. Madsen, J. Kirk Johansen, B. S. Larsen, J. J. Struijk, L. Frost, N. R. Holm, E. H. Christiansen, H. E. Botker, and M. Bøttcher, ''Diagnostic performance of an acoustic-based system for coronary artery disease risk stratification,'' *Heart*, vol. 104, no. 11, pp. 928–935, Jun. 2018.

[13] S. Winther, S. E. Schmidt, N. R. Holm, E. Toft, J. J. Struijk, H. E. Bøtker, and M. Bøttcher, ''Diagnosing coronary artery disease by sound analysis from coronary stenosis induced turbulent blood flow: Diagnostic performance in patients with stable angina pectoris,'' *Int. J. Cardiovascular Imag.*, vol. 32, no. 2, pp. 235–245, Feb. 2016.

[14] M. K. Zia, B. Griffel, J. L. Semmlow, V. Fridman, and C. Saponieri, ''Noise detection and elimination for improved acoustic detection of coronary artery disease,'' *J. Mech. Med. And Biol.*, vol. 12, no. 2, p. 17, Apr. 2012.

[15] J. L. Semmlow, M. Akay, and W. Welkowitz, ''Noninvasive detection of coronary artery disease using parametric spectral analysis methods,'' *IEEE Eng. Med. Biol. Mag.*, vol. 9, no. 1, pp. 33–36, Mar. 1990.

[16] M. Akay, J. L. Semmlow, W. Welkowitz, M. D. Bauer, and J. B. Kostis, ''Detection of coronary occlusions using autoregressive modeling of diastolic heart sounds,'' *IEEE Trans. Biomed. Eng.*, vol. 37, no. 4, pp. 366–373, Apr. 1990.

[17] Z. D. Zhao, ''Noninvasive diagnosis of coronary heart disease based on diastolic heart sound signal analysis and feature extraction,'' Tech. Rep., 2004.

[18] H. X. Li, Y. F. Ren, G. J. Zhang, R. X. Wang, X. Y. Zhang, T. Zhang, L. S. Zhang, J. G. Cui, Q. D. Xu, and S. C. Duan, ''Design of a high SNR electronic heart sound sensor based on a MEMS bionic hydrophone,'' *AIP Adv.*, vol. 9, no. 1, p. 10, Jan. 2019.

[19] H. Z. M. Shafri and M. R. M. Yusof, ''Determination of optimal wavelet denoising parameters for red edge feature extraction from hyperspectral data,'' *J. Appl. Remote Sens.*, vol. 3, p. 19, May 2009.

[20] J. Gilles, ''Empirical wavelet transform,'' *IEEE Trans. Signal Process.*, vol. 61, no. 16, pp. 3999–4010, Aug. 2013.

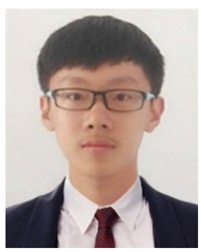
[21] V. Nivitha Varghees and K. I. Ramachandran, ''Effective heart sound segmentation and murmur classification using empirical wavelet transform and instantaneous phase for electronic stethoscope,'' *IEEE Sensors J.*, vol. 17, no. 12, pp. 3861–3872, Jun. 2017.

[22] H. Li, Y. Ren, G. Zhang, R. Wang, J. Cui, and W. Zhang, ''Detection and classification of abnormities of first heart sound using empirical wavelet transform,'' *IEEE Access*, vol. 7, pp. 139643–139652, 2019.

HAIXIA LI was born in 1983. She received the Ph.D. degree in instrument science and technology from the North University of China. She is currently with an Associate Professor with Xinzhou Teachers University. Her research interests include design of micro-electro-mechanical system (MEMS) sensitive units and heart sound signal processing.

GUOFENG REN was born in Xinzhou, Shanxi, China, in 1979. He received the Ph.D. degree from the Taiyuan University of Technology. He is currently an Associate Professor with Xinzhou Teachers University. His main research interests include emotional speech signal processing and speech pronunciation mechanism.

XIAOPU YU is currently pursuing the master's degree in cardiovascular internal medicine with the Shanxi Medical University of China. He is attending resident standardization training in the second hospital of Shanxi Medical University



DONGYING WANG is currently pursuing the master's degree with the Shanxi Medical University of China. His main research direction is the foundation and clinical of coronary heart disease. He is also a member of the Chinese Pathophysiology Society.

SHIZHE WU is currently a Senior Student with the Zhida Ivy League Middle School, Taiyuan, Shanxi, China. He has a wide range of hobbies and is good at building mechanical model and circuit model. He acted as an experimental assistant in this project, responsible for recording and organizing experimental data.