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Isolation of Systolic Heart Murmurs Using Wavelet Transform and Energy Index

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Abstract

The paper presents the results of a signal processing approach to detect and isolate systolic murmurs. The identification of the first and second heart sounds and separating systole and diastole from a complete cardiac cycle were successfully carried out through wavelet analysis using an orthogonal Daubechies (db6) wavelet as the mother wavelet. At the fifth level of decomposition, S1 and S2 were effectively separated from systolic heart murmurs. A quantitative measure of signal energy was developed and used to determine the boundaries of S1 and S2 sounds and to isolate systolic murmurs. The energy index can be also used to delineate the intensity and configuration of a systolic murmur. We have examined and reported in this paper the performance of this approach by examining few known clinical systolic murmurs: atrial septal defect (ASD), ventricular septal defect (VSD), and mitral valve prolapse (MVP).

1. Introduction

The heart acts as a pump to move blood through the arterial circulation by rhythmically contracting (systole) and relaxing (diastole). Through decades of integrated efforts from many disciplines, modern electronics embedded with advanced signal processing algorithms and clinical intelligence, were developed to improve our knowledge of the anatomy and physiology of the cardiovascular system. For example, electrocardiogram (ECG/EKG), echocardiography, magnetic resonance imaging (MRI), and cardiac catheterization have been routinely used in hospitals and clinics. Heart sounds and murmurs, the auditory events acquired from the heart with a stethoscope, on the other hand, carry other types of information regarding the condition of the anatomy and physiology of the cardiovascular system, i.e., vibrations of heart walls originated from the opening and closure of cardiac valves and the turbulent flow of blood. Although the precise mechanism that produces heart sounds and murmurs is still a subject of research, cardiac auscultation has been the most popular bedside investigative tool used by physicians to detect alternations of the cardiovascular system [1]-[2].

The challenge involved in cardiac auscultation is complicated. To begin, the effectiveness of cardiac auscultation depends heavily on the physician's auditory sensitivity and the quality of the auscultation equipment. While there are established descriptions of the major heart sound and murmur characteristics, such as timing, intensity, duration, pitch, and configuration [1]-[2], their interpretation is qualitative, rather than quantitative. Even in modern clinical practice, cardiac auscultation is still susceptible to the physician's clinical experience as a result of the lack of quantitative measures and the sensitivity of the human ear.

This paper presents a new signal processing approach to isolate systolic heart murmurs based on wavelet transform [3] - [7] and an energy index (defined in the following section). Wavelet transform based analysis has been used to examine heart sound signals by many researchers [8] - [12]. Systolic murmurs appear between the first (S1) and the second (S2) heart sound; diastolic murmurs are heard after S2 and before the next S1 sound [2]. Segmentation of the heart cycle into systole and diastole is an important first step in heart signal analysis. The suggested approach demonstrates the isolation of the systole interval and the detection of systolic murmur onset and duration. The importance of the presented approach lays in the fact that recognition and quantification of heart murmur characteristics can be performed efficiently only when the exact onset and duration of the heart murmur are known. Therefore, this method can be beneficial for the analysis of a broad range of heart defects using signal processing.

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To facilitate the processing, each complete cardiac cycle was first divided into several segments containing its main components: S1, systole, S2, and diastole. S1 and S2 can be recognized based on known clinical observations, e.g., S1 is louder than S2 at the apex while S2 is louder than S1 at the base (upper liming of the heart) [2]; the systole period is usually longer than the diastole period. To distinguish S1 and S2 and to isolate the heart murmur, pitch (frequency) is a valuable measure since heart murmurs generally exhibit higher frequency contents than those of S1 and S2 [2], [13]-[14]. Therefore, S1 and S2 can be recognized by using a multi-resolution discrete wavelet transform [6]-[7]. A properly chosen mother wavelet and scaling depth are important for differentiation between the frequency distributions of the murmur and the heart sounds. In our paper, we found that the Daubechies wavelet (db6) at the fifth scale provides a satisfactory filtering effect.

Without loss of generality, the effectiveness of the suggested new approach was demonstrated via several systolic heart murmurs having clinical significance, including atrial septal defect (ASD), ventricular septal defect (VSD), mitral valve prolapse (MVP), and Still's murmur.

2. Methods

2.1 Wavelet Transform

In recent years, researchers in applied mathematics and signal processing have developed powerful wavelet methods for the multi-scale representation and analysis of signals [3]-[7]. Wavelet analysis differs from the traditional Fourier transform by that a signal is treated as a combination of scaled and delayed wavelets. For a given signal *x(t)*, the continuous-time wavelet transform (CWT) is given below

$$CWT_x(\tau,a)=\frac{1}{\sqrt{a}}\int x(t)h^*\left(\frac{t-\tau}{a}\right)dt \qquad (1)$$

where $h(t-\tau/a)$ is the scaled, shifted version of a mother wavelet [7]. Wavelet analysis can localize information in the time-frequency domain; in particular, it can trade time-resolution for frequency-resolution when necessary, which makes it useful for the analysis of non-stationary signals. Heart sound signals have frequency contents that change over time and therefore a joint time-frequency wavelet transform (WT) is an appropriate choice for heart sound analysis [8]-[12].

WT uses short data windows at high frequency signals and long data windows for low frequency components. This unique performance is useful in heart sound analysis can facilitate the separation of the underlying signal into low-frequency heart sounds S1 and S2 and high-frequency murmurs. WT based methods have become popular in analyzing cardiovascular sounds in recent years [8]. Wavelet decomposition in combination with a simplicity-based adaptive filter was used by Kumar [10] for boundary identification of S1 and S2. Turbulent sounds caused by femoral artery stenosis were analyzed by Akay [9] using a wavelet transform method to decompose the flow sounds into details and approximations. Tovar-Corona utilized continuous wavelet transformations to develop spectrogram looking maps of heart signals that present wavelet scale variation in time (scaleograms) [12].

2.2. Separating murmurs from S1 and S2 via discrete wavelet transform (DWT)

A WT based multi-resolution signal decomposition was proposed by Mallat [6], which can be used in identifying the boundaries of heart sounds S1 and S2. The Mallat algorithm uses dyadic (based on powers of two) scales and positions to make the analysis efficient without loss of accuracy. For example, for a time series sequence representing the waveform of cardiac cycles, a lower resolution signal can be derived by low-pass filtering with a half-band low-pass filter, where two outputs (details and approximations) are separated to high and low frequency components.

The effectiveness of WT filtering hinges upon two key parameters: the chosen mother wavelet and the scale depth applied. Each mother wavelet has its own center frequency. As the scale increases, the frequency band of the retained signal decreases as follows:

$$F_a=\frac{F_c}{a\Delta}, \qquad (2)$$

where F_c is the center frequency of the mother wavelet in Hz; a and Δ are the scale and the sampling period, respectively. F_a is a pseudo-frequency that corresponds to the scale a.

Heart sounds S1 and S2 sounds have a frequency range roughly below the band of 60-80 Hz, and heart murmurs are mostly higher than 125 Hz. Therefore, to effectively separate S1 and S1 from heart murmurs, we have chosen *db6* wavelet and the fifth scale level because *db6* wavelet resembles S1 and S2. The center frequency of *db6* is approximately 0.7273 Hz. The frequency band associated with each approximation level can be estimated using (2). Table 1 summarizes the estimation up to the sixth level. At the fifth level of decomposition (scale=32), the corresponding pseudo-frequency is lower than the murmurs and higher than S1 and S2 hearts sounds. Murmurs with high-frequency contents are expected to be eliminated using this WT based filtering, while S1 and S2 sounds will remain.

Table 1. Pseudo-frequency bands of six approximation levels (A_1–A_6) using *db6* WT.

Level (Scale)	A_1 (2)	A_2 (4)	A_3 (8)	A_4 (16)	A_5 (32)	A_6 (64)
Frequency Band (Hz)	1818 to 909	909 to 455	455 to 227	227 to 114	114 to 57	57 to 28

2.3. Isolation of systole and quantification of murmurs using an energy index

The intensity of heart murmur is normally graded to six different levels according to the Levine scale [1], which has been observed in clinical practice for more than 70 years. Sound intensity, by definition, is the measurement of the sound power per unit area (e.g., watts/cm^2). To characterize the systolic murmur by its intensity, we used an energy index shown below

$$engy = \frac{1}{N}\sum_{n=1}^{N}(x(n) - \mu_x)^2, \qquad (3)$$

where $\{x(n)\}$ is the time series representing heart sounds and the murmur, and μ_x is the sample mean. The energy index is the mean-squared value of a signal and can be used effectively to determine the systole interval and to provide the murmur intensity profile during the systole. The following steps are necessary to isolate the systole:

- Perform WT filtering described in Section 2.2.
- Divide the complete cardiac cycle into smaller data segments of equal length and calculate the energy index for each segment using (3).
- Mark S1 (S2) boundary at about 7.3% of the peak energy of S1 (S2), which should be within 55 milliseconds from the heart sound peak.

The confirmed S1 and S2 boundaries also mark the beginning and end of systole. The systole murmur, on the other hand, can also be detected using the energy index against another predetermined threshold, which is set at 25% of the mean energy of the whole systole. The systole interval is examined sample by sample and a murmur is marked when the sample energy is higher than the threshold. The onset and the end of the murmur are determined by this approach.

3. Results and Discussion

Without loss of generality, we examined the performance of the proposed WT based algorithm using both simulated and clinically recorded heart sound episodes, such as ASD, VSD, MVP, and Still's murmur. We present the results for a computer-simulated ASD episode and a clinically-recorded MVP episode obtained from [2].

The top trace in Fig.1 shows the phonocardiogram of ASD for three cardiac cycles. The bottom trace in Fig.1 displays the filtered result using the *db6* wavelet at the fifth level approximation (scale=32) through DWT. As observed in the fifth level approximation, the systolic murmur was greatly reduced while S1 and S2 were less affected. This result can effectively facilitate the isolation of the systole period.

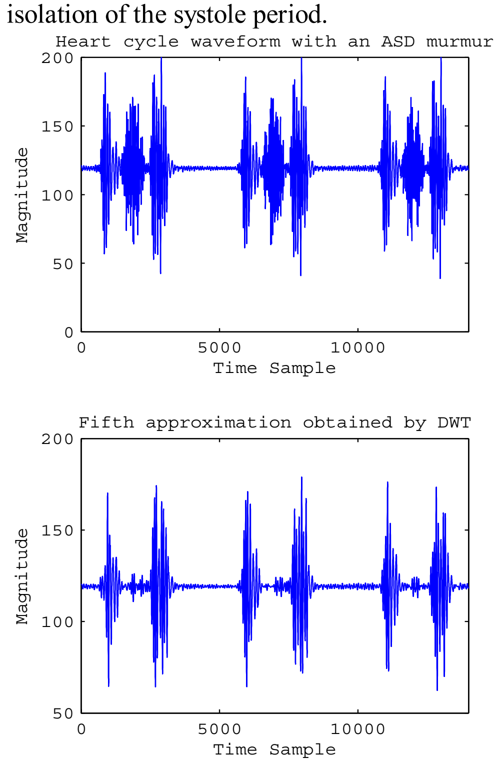

Figure 1. Digitized heart signal waveform containing an Atrial Septal Defect (ASD) and the fifth level of decomposition.

Fig. 2A shows a single systole of ASD after DWT decomposition. Through the steps listed in Section 2.3, the energy content of the approximation at the fifth level was computed and shown in Fig. 2B, where the onset and end of the systole can be easily identified.

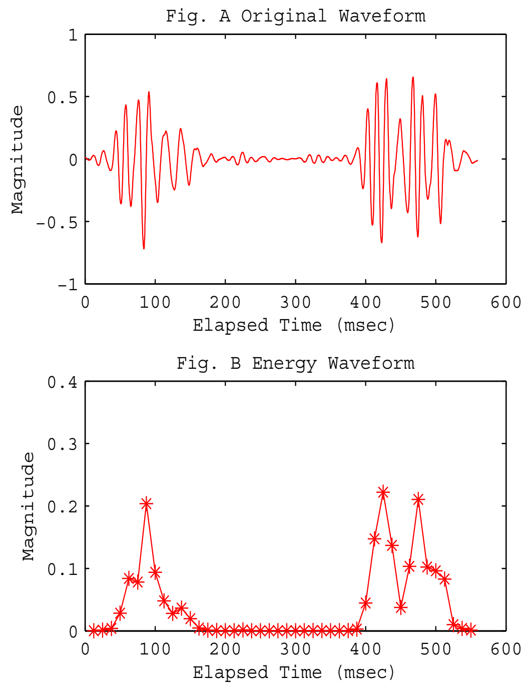

Figure 2. (A). ASD waveform after DWT and (B) the energy index profile.

To detect the boundaries of S1 and S2, the magnitude of the energy waveform was compared to the empirically determined energy threshold. The isolated systole is shown in Fig. 3A. After the systole was isolated, the energy index was computed using (3); the energy profile is displayed in Fig. 3B.

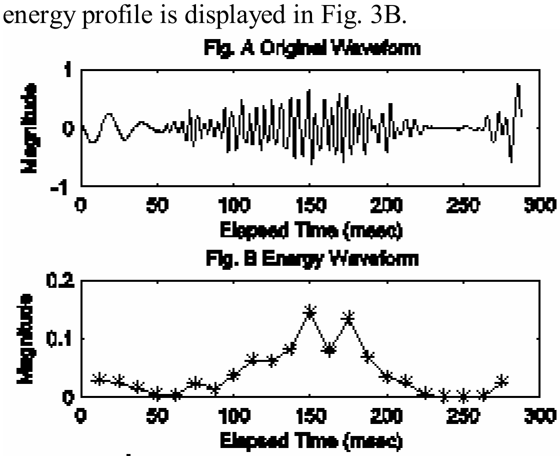

Figure 3. A. ASD waveform in systole and B. the energy profile during systole.

The systole energy waveform is examined sample by sample to detect the increased energy level of the present murmur. An ASD waveform is decomposed using WT into various sections depicted in Fig. 4.

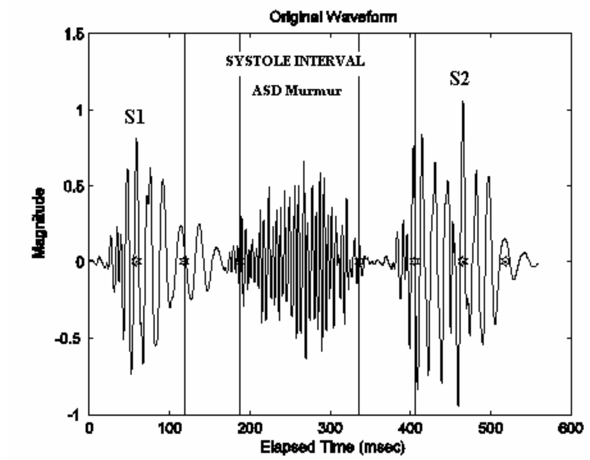

Figure 4. ASD heart signal decomposed into S1 sound, systolic murmur, and S2 sound

The same procedure was performed for several other systolic heart murmurs. In all cases, systolic murmurs were correctly detected and isolated with good accuracy. Fig.5 shows the result of the WT analysis of a sound episode of mitral valve prolapse (MVP) murmur.

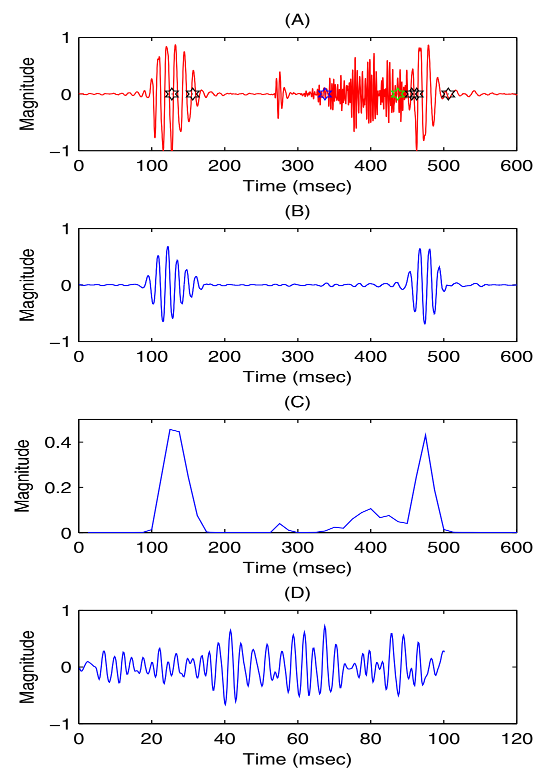

Figure 5. Segmentation of an MVP episode: (A) Original heart signal; (B) Fifth level of DWT decomposition; (C) Energy index profile; (D) Detected and isolated MVP murmur

4. Conclusion

Clinical diagnosis of cardiovascular alternations through auscultation of heart sounds is a highly delicate professional skill. Many factors contribute to the challenge of becoming masterful in cardiac auscultation. Our study of WT based signal processing algorithm provides a possibility of making cardiac auscultation less subjective to personal differences, even though our study focus was on a small set of systolic murmurs. Nevertheless, we feel comfortable to draw the following statements:

1. Heart sounds and murmurs are not narrow-band signals. WT based algorithm with a carefully selected mother wavelet that resembles the heart sounds or murmurs can be very effective to detect and isolate S1, S2 and murmurs.

2. Daubechies wavelet (*db6*) is an appropriate mother wavelet for heart sound analysis.

3. The energy index can accurately reflect the intensity of heart sounds and murmurs. Furthermore, it is also possible to use the energy index to provide a satisfactory description regarding the configuration of a murmur.

4. Isolation of systole and detecting the onset of systolic murmurs were performed using thresholds. These thresholds were generated by empirical tests. Better assessment is necessary to avoid subjective differences.

5. WT based decomposition, combined with the energy index, proves to be effective in analyzing systolic murmurs. It can be extended to diastolic murmurs as well with minor modifications.

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