ICSP2012 Proceedings

A Fast Heart Sounds Detection and Heart Murmur Classification Algorithm

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Abstract— **This paper extends our previous studies and presents a fast, automatic cardiac auscultation scoring system that effectively identifies the first and second heart sounds (S_1 and S_2) and extracts clinical features of heart murmurs to assist clinical diagnosis. Using the indices derived from AR modeling, the underlying scoring system is capable of detecting and identifying S_1 and S_2, dissecting the systole and the diastole for further analysis and extracting heart murmurs features found within, such as timing, duration, loudness (intensity), pitch and shape of murmurs. To achieve a broader spectrum of application, only the relative duration difference between systole and diastole was used as the *a priori* information to identify S_1 and S_2. This algorithm is particularly suited for an embedded system implementation with ease of calculations while maintaining accuracy and effectiveness. The suggested has been successfully evaluated with multiple cardiac cycles, where each systole and diastole was accurately identified and isolated. The performance of the approach has met good success using clinical data from patients with a variety of systolic murmur episodes.**

Keywords- heart sounds; heart murmurs; AR modeling; data segmentation

I. INTRODUCTION

Heart disease is the number one cause for adult death in many countries, primarily because of the rapidly changed eating habits and increased stress of a modern society. The stethoscope—invented in 1816, unlike other modern and advanced diagnostic equipment, such as the MRI, CAT, and ultrasound (echocardiogram)—still remains the primary bedside diagnostic tool mainly because of the unique information it has provided for clinical diagnosis. However, the effectiveness of cardiac auscultation is heavily subject to an individual physician's experience and skill. Today, a significant percentage of physicians cannot perform effective and accurate cardiac auscultation (a sadly well-known situation admitted to by the American Heart Association) that has contributed to many patients being referred to cardiologists for further medical examinations due to abnormal findings in cardiac auscultation that turn out to be normal. Such a dire situation clearly indicates the urgent need for improved cardiac auscultation accuracy [1]. Taking advantage of modern computers and signal processing developments presents a natural path for pursuit.

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While the high false alarm rate exposes the limitation of human-dependent auscultation, other related causes, such as a physician's inexperience and poor quality of hearing instruments, also adversely reduce diagnosis accuracy. The underlying paper extends our previous studies [8]-[11] in heart sounds and murmurs and presents a fast identification and classification scoring system with little or no human supervision. The main goal of the computer-aided auscultation approach is to provide consistent and reliable delineation of heart murmurs to support physicians in evaluating human cardiovascular conditions and identifying signs of abnormal alternations or heart diseases [3]. In particular, the approach can provide quantitative descriptions of heart murmur features, including timing, duration, pitch, intensity, and shape configuration [1], [3], [7].

When the heart sounds are analyzed with the ECG, the first heart sound S_1 (snap sounds caused by the closure of mitral and tricuspid valves) can be immediately identified after the QRS complex, while S_2 (the closure of aortic and pulmonary valves) occurs following the T-wave in ECG [4]. In a situation where the ECG is not available, the challenge of a computer based heart sound and murmur analysis deepens and becomes more complex and, unavoidably, additional information regarding the cardiac operation must be adopted. For example, a typical observation is that the duration of the systole is usually shorter than that of the diastole in most people. We have adopted this observation in this study to differentiate S_1 from S_2. Once S_1 and S_2 are identified, systole and diastole can be labeled and dissected for additional analysis.

To untrained ears, heart murmurs are noise-like auditory vibrations caused by the turbulence of blood flowing within the cardiovascular system from various heart diseases. The cause of turbulent flow can be attributed to many possible anatomical alternations [1]-[3],[7], such as blood flowing through a narrowed orifice (aortic stenosis), blood flowing into a chamber of larger size from a smaller diameter (aortic aneurysm), rapid and voluminous blood flow, or a combination of other anatomical alternations. In an era where modern diagnostic tools are quickly emerging, cardiac auscultation of turbulence caused by vibrations can reveal a unique aspect of the cardiovascular information not obtainable

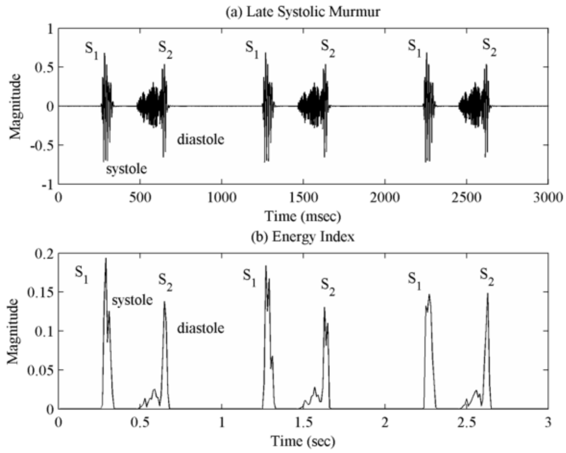

Figure 1. Heart sounds and late systolic murmur episodes

by other diagnostic devices. Therefore, as a traditional tool for more than hundreds of year, cardiac auscultation remains a valuable bedside investigative process for physicians [3] - [4], [7]. Our goal is to make it more effective and accurate.

To effectively assist cardiac auscultation, important heart sound and murmur features must be accurately provided with an ease of interpretation. Accordingly, our approach is to generate accurate heart murmur features of timing, duration, pitch, intensity, and shape. The performance of our scoring system has been evaluated using a variety of systolic and diastolic murmur episodes from patients with documented heart problems. They include early-systolic, mid-systolic, late-systolic, holo-systolic, early-diastolic, and mid-diastolic murmurs [7]. The scoring system provides timing results in milliseconds regarding the onset and duration of detected murmurs within systole or diastole; the murmur pitch is provided with the averaged murmur frequency in hertz; murmur intensity and grading is described by the percentage of energy with respect to S_2; and murmur shape is delineated as crescendo, decrescendo, crescendo-decrescendo, or plateau.

II. Methods

When cardiac auscultation is performed without the ECG recording for a timing reference, as in the case for our study, the first and second heart sounds must be identified through other means. To fix the idea, we can examine a late systolic murmur episode shown in Fig. 1(a). The murmur occurs in the late half of the systole and merges with the second heart sound S_2. The observed murmur amplitude has an increasing profile, i.e., the shape of crescendo. The systole duration from $S_1 \rightarrow S_2$ is shorter than the duration of diastole from $S_2 \rightarrow S_1$. We used the duration difference to differentiate S_1 and S_2.

A. Identification of S_1 and S_2

Since S_1 and S_2 can be identified by their distinctly larger amplitude, in our analysis, we divided the heart sound and murmur signal into short segments of equal length of 10 milliseconds (msec) and computed an energy index function for each short segment using (1).

$$ENGY_n = \frac{1}{N}\sum_{k=1}^{N}(x(k)-\mu_n)^2 \qquad (1)$$

where μ_n is the mean value of heart sound signal $x(k)$ within the n^{th} segment. The energy index function for the three complete cardiac cycles of the early systolic murmur is shown in Fig. 1(b). The marked peaks in Fig.1(b), indicating the locations of S_1 and S_2, can be immediately marked. Through comparison of the distances between marks, S_1 and S_2 can be correctly labeled. In certain heart sound and murmur episodes where S_1 is louder than S_2, the labeling process can be easier and more accurate by incorporating this fact. The process of identification and labeling is equally effective if with the knowledge that S_2 is louder than S_1. Another useful measure to identify is the average absolute value of a short segment.

$$ABV_n = \frac{1}{N}\sum_{k=1}^{N}| x(k)-\mu_n |, \qquad (2)$$

where μ_n represents the mean value of the n^{th} segment. The *ABV* index is easily calculated and serves as a good indicator to describe the murmur shape. We have found in our evaluation examples that both *ENGY* and *ABV* serve as good indices to identify S_1 and S_2.

B. Dissecting Systole and Diastole

Once heart sounds S_1 and S_2 are identified and labeled, systole and diastole can be segmented between borders of S_1 and S_2. Durations of S_1 and S_2 lie between 55 to 65 milliseconds in general. Without loss of generality, we simplified the delineation of the S_1 and S_2 boundary within 30-msec of the signal before the marked peaks in this energy index and 30-msec that follows the peak, or when the ENGY or ABV index drops to less than 10% of the marked peak value.

C. Classification of Murmur(s)

Murmurs can be identified and labeled if the dissected systole/diastole exhibits significant activity above a normal baseline value. In the current study, a heart murmur is called when the energy index is larger than an empirically determined threshold, which is tied to the energy of S_2. The energy content of the systole interval was examined segment by segment and, as soon as its value rose above the pre-determined threshold after few consecutive segments, a murmur was called and the murmur onset was marked. The end of the murmur was detected similarly. As soon as the energy index was reduced below the set threshold, the end of the murmur was denoted. The murmur *timing* was determined as the time between the waning side of S_1 to the murmur onset. Murmur *duration* was determined as the time between the murmur onset and its end. As observed in Fig.1(b), the murmurs only occur during systoles and its duration is about 150 milliseconds and merges with S_2 before it ends, i.e., a typical late systolic murmur. Through our analysis, the onset of murmur and the systole

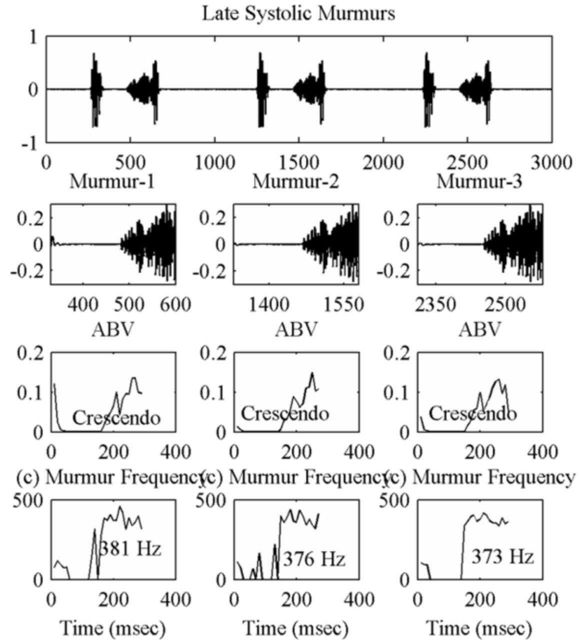

Figure 2. Late systolic murmur and analysis results

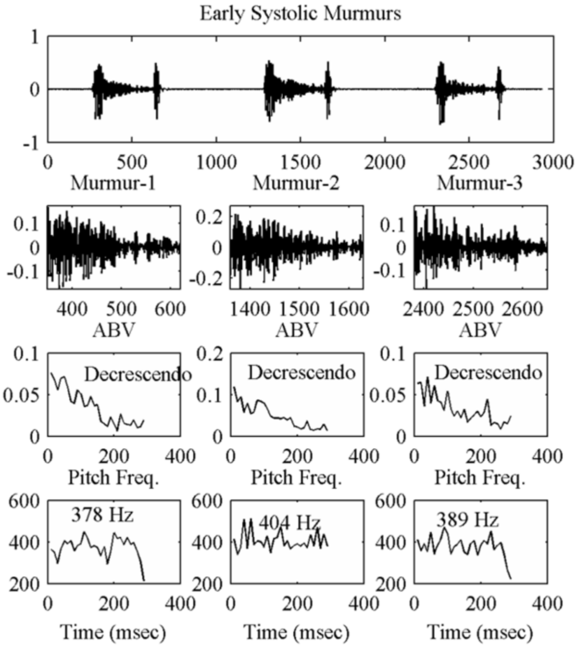

Figure 3.Early systolic murmur and analysis results

duration are presented in milliseconds. Therefore, early-, mid-, or late-systolic murmur can be quantitatively determined.

The pitch frequency of the detected murmur in Fig.2 can be effectively estimated through the second-order AR model (3) coefficients [8]-[10] without referring to the spectrum estimation and Fourier transform.

$$e_k = x(k) - a_1 x(k-1) - a_2 x(k-2) \tag{3}$$

The AR model coefficients are estimated by minimizing the mean squared prediction errors in (4) using the fast Burg's time series analysis algorithm [5]. The murmur pitch frequency can be estimated as follows

$$pitch = \frac{f_s}{2\pi} \tan^{-1}\left(\frac{\sqrt{4a_2 - a_1^2}}{a_1}\right) \tag{4}$$

where f_s is the sampling frequency.

Heart murmur features of the pitch frequency and shape were computed using (1), (2) and (4). Through the algorithm implemented in our study, Fig.2 shows the analysis results of the three consecutive late systolic murmurs in Fig.1. The duration of the late systolic murmurs is about 110 msec; the shape delineated by both the *ENGY* and *ABV* indices is a crescendo configuration; the average murmur frequency was estimated between 373 to 381 hertz (high pitch).

The murmur intensity (loudness) is graded in clinical diagnosis from a minimum of Grade-1 to the maximum of Grade-5. The grades are described in Table I. We divided the murmur energy by the second heart sound S_2 energy and used the percentage to determine the grade of a detected murmur. The decision rule is described in the third column of Table I.

We calculated the average intensity for each extracted late systolic murmur and the intensity is between 55-57 % of S_2 energy, i.e., grade-3 late systolic murmur. It is to be noted, however, that when thresholds used for determining the onsets and durations of S_1 and S_2 and murmurs were modified, the scoring results of heart sounds and murmurs also differed. Nevertheless, minor alternations did not change the main features of detected murmurs and result interpretations.

TABLE I. MURMUR INTENSITY GRADING CRITERIA

Grade	Clinical Description	% of S_2 Energy
1	quiet murmur that can be heard only after careful auscultation over a localized area	≤ 20 %
2	quiet murmur that is heard immediately once the stethoscope is placed over its localized point of maximal intensity (PMI)	≥ 20 % but ≤ 45%
3	loud murmur heard over a widespread area, with no thrill palpable	≥ 45 % but ≤ 75%
4	loud murmur with an associated precordial thrill	≥ 75 % but ≤ 100%
5	murmur sufficiently loud that it can be heard without the stethoscope raise just off the chest surface	≥ 100 %

III. RESULTS AND DISCUSSION

Figure 3 summarizes the results of another evaluation example of early systolic murmurs. We have tested the suggested approach with clinical data recorded from patients with diagnosed heart diseases [7]. They are displayed in Fig.4. Performance results are described in the following.

(a) Early systolic murmur – the murmur occurs in the systole; it starts immediately after S_1 where the onset of

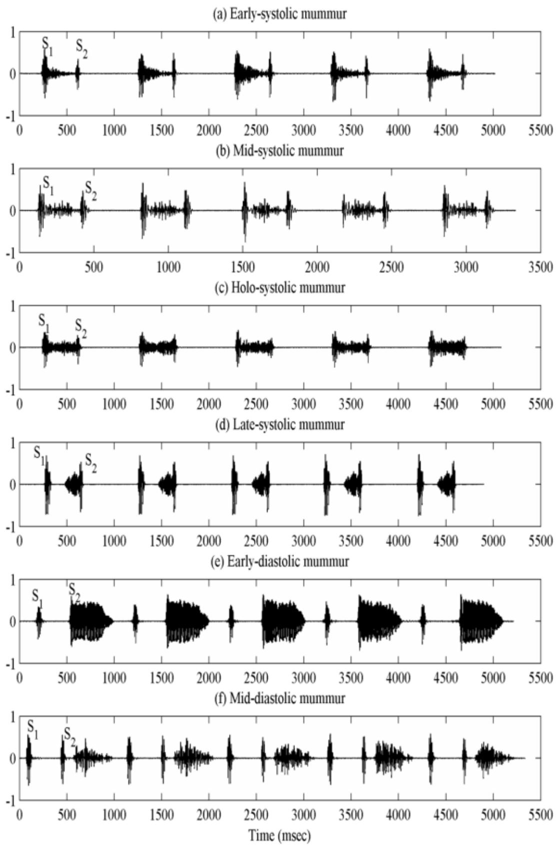

Figure 4. Systolic and diastolic heart murmurs

the murmur overlaps with S_1; murmur duration is from 150 to 220 msec; high pitch frequency of 378 to 404 Hz; the murmur shape is decrescendo; the murmur has an intensity of 35 to 45 of S_2, i.e., grade-2/3 murmur.

(b) Mid-systolic murmur – the murmur occurs after S_1 and ends before the onset of S_2; the pitch frequency is low from 152 to 157 Hz; the murmur shape is determined as crescendo-decrescendo; the murmur is grade-2 but close to grade-3 murmur.

(c) Holosystolic murmur – the murmur appears throughout the whole systole for a length of 260 to 280-msec, i.e., holosystolic murmur; the pitch frequency is estimated high between 360 to 383 Hz; the murmur shape is generally plateau; the murmur intensity is more than 60% of S_2 energy, i.e., a grade-3 murmur.

(d) Late systolic murmur – the murmur appears 160-170 msec after S_1 and it merges with S_2; the duration is roughly 110 msec; the murmur has a high pitch between 373 to 381 Hz; it has a shape of crescendo; the murmur intensity is more than 55% of S_2 and graded at level 3.

(e) Early diastolic murmur – the onset of the murmur overlaps with S_2 in diastole, categorized as an early diastolic murmur; it has a low pitch frequency of 121 Hz and a decrescendo shape; the murmur intensity is 88% of S_2 and is a grade-4 murmur.

(f) Mid-diastolic murmur – the murmur occurs at 100-msec after S_2 and ends before S_1 of the next systole cycle. It sustains more than 300-msec. It is a mid-systolic murmur that has a crescendo-decrescendo shape and low pitch frequency of 102 Hz.

We understand that the cases presented here represent only a small segment of the whole cardiac auscultation domain. However, the experience and results thus accumulated shed a light to the direction for improvements. One particular challenge that lies ahead is establishing a statistical confidence of system performance because of the difficulty of getting a sufficient quantity of clinical data. In summary, the underlying approach presents a fast, accurate heart sound identification and murmur classification algorithm. It is straightforward to implement and particulary suited for embeded systems; it can process multiple cardiac cycles automatically with little or no human supervision; and it has demonstrated the capability to generate quantitative heart murmur features which are consistent with clinical diagnoses.

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