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An adaptive singular spectrum analysis approach to murmur detection from heart sounds

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ABSTRACT

Murmur is the result of various heart abnormalities. A new robust approach for separation of murmur from heart sound has been suggested in this article. Singular spectrum analysis (SSA) has been adapted to the changes in the statistical properties of the data and effectively used for detection of murmur from single-channel heart sound (HS) signals. Incorporating a cleverly selected a priori within the SSA reconstruction process, results in an accurate separation of normal HS from the murmur segment. Another contribution of this work is selection of the correct subspace of the desired signal component automatically. In addition, the subspace size can be identified iteratively. A number of HS signals with murmur have been processed using the proposed adaptive SSA (ASSA) technique and the results have been quantified both objectively and subjectively.

1. Introduction

The demand for automatic detection of murmur from auscultation of heart sound has been addressed by researchers and clinicians recently [1–6]. In [1] patients with previously diagnosed hypertrophic cardiomyopathy (HCM) (both obstructive and non-obstructive) have been assessed for the presence of heart murmur, murmur characteristics, change in murmur loudness with postural change, and detectability of murmurs by an automated system. In [2] the maximum intensity of the systolic murmur, its average frequency, and the mean spectral power were quantified. The frequency at the point with the highest sound intensity in the spectrum and its time from the first heart sound, the highest frequency, and frequency range were also determined. Separation of murmur in this method however is based on segmentation and classification of the data and does not incorporate the basic heart sound and the murmur detailed statistical parameters (within the overlapped regions) into account. In the method proposed in [3] the spectrogram is used as an input to a multiple layer perceptron (MLP) neural network trained to detect the presence of heart murmurs. Once the murmur is detected they are classified into seven classes depending on their timing within the cardiac cycle using smoothed pseudo Wigner–Ville distribution. The method is simple and confirms that most of the signals' information lies in the time-frequency space. In this method the resolution constraint and the time-frequency overlaps of the signal components are the major drawbacks. Other workers applied some simple classifier to detect and classify the systolic murmur for phonocardiogram screening [4]. In another approach [6] the above two systems are somehow combined and a neural network is used for classification of normal heart sound and murmur. Some other similar methods mainly based on time-frequency analysis and feature classification have also been reported [3].

A heart murmur is an extra or unusual sound heard during and in between two heartbeats. Murmurs occur when a valve does not close tightly (such as with mitral regurgitation) and blood leaks backward. They also can occur when the blood flows through a narrowed or stiff valve [5]. The murmurs' sound ranges from very faint to very loud. They sometimes sound like a whooshing or swishing noise. Normal heartbeats make a "lub-dupp" or "lub-dup" sound. This is the sound of the heart valves closing as blood moves through the heart. Murmur, on the other hand, has a noise type or "Puff" sound and stretches from start of the heart sound for few seconds or even the entire interval between the two heart beats.

The heart sounds and heart murmurs may be recorded using electronic stethoscope connected to PC via an ADC and amplifier interface. Cardiac murmurs can be divided into three categories based on where they occur in the cardiac cycle. Short, quiet systolic murmurs are generally benign or innocent. Long systolic murmurs, diastolic murmurs and continuous murmurs are generally pathologic. People who have benign heart murmurs have normal hearts. On the other hand, people who have abnormal murmurs may have other signs or symptoms of heart problems. Most abnormal mur-

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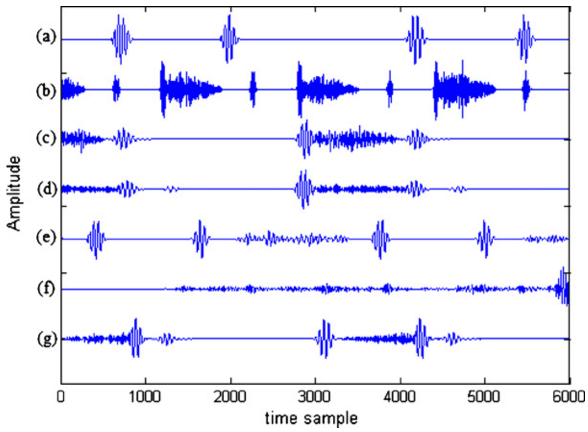

Fig. 1. Normal heart sound (a) and heart sounds with (b) aortic regurgitation murmur, (c) aortic stenosis murmur, (d) mitral regurgitation murmur, (e) mitral stenosis murmur, (f) precardial friction murmur, and (g) pulmonary stenosis murmur.

murs in children are due to congential heart defects. These are heart defects that are present at birth. In adults, abnormal murmurs are most often due to heart valve problems caused by infection, disease, or aging. Fig. 1 shows the sound signal of a normal heart and a number of popular sounds of heart with murmur [7]. These signals have been recorded with 22 kHz sampling frequency using a Welch Allyn Tycos stethoscope. The stethoscope was connected to the PC through a multichannel ADC card and signal conditioner and amplifier (Traveler-MK3 Portable bus-powered audio interface). The maximum frequency band of these signals is below 300 Hz. Therefore, they have been down-sampled here to 1600 sample/s in order to reduce the computation cost while no information is lost. The most important types of murmur are briefly described here.

Aortic regurgitation is the diastolic flow of blood from the aorta into the left ventricle. The hallmark of aortic regurgitation or insufficiency is a high-pitched decrescendo diastolic murmur at the left sternal border after the second heart sound. This abnormality causes significant morbidity within few years after diagnosis mainly after the age of 50 [7]. Aortic stenosis is a narrowing or obstruction of the aortic valve. The aortic component of the second heart sound, is usually diminished or absent because the aortic valve is calcified and immobile and/or aortic ejection is prolonged and it is obscured by the prolonged systolic ejection murmur. An ejection click is common in children and young adults with congenital aortic stenosis but rare in elderly individuals with acquired calcific aortic stenosis. This sound occurs approximately 40–60 ms after the onset of S_1 and is frequently heard best along the mid to lower left sternal border. The more severe the stenosis, the longer the duration of the murmur and the more likely it peaks at mid-to-late systole. When the left ventricle fails and cardiac output falls, the aortic stenosis murmur becomes softer and may be barely audible. Atrial fibrillation with short R–R intervals can also decrease the murmur intensity or make it appear absent [7]. Mitral regurgitation is a high-pitched holosystolic murmur beginning with the first heart sound and extending to the second heart sound. The intensity usually is constant throughout systolic ejection, often radiating to the axilla. The harshness of the murmur does not correlate with the magnitude of the valvular defect. Patients with severe disease often have a third heart sound. In acute mitral regurgitation, the examination usually is consistent with acute pulmonary edema and left ventricular failure. The murmur often is harsh. It may be heard over the back of the neck, vertebra, and/or sacrum and may radiate to the axilla, back, and left sternal border [7]. Mitral stenosis is a narrowing of the inlet valve into the left ventricle that prevents proper opening during diastolic filling. The most common cause of mitral stenosis is rheumatic fever [7]. In examination of the subjects with mitral stenosis often low-pitched, rumbling murmur is observed. The duration, and not intensity, of the murmur is a guide to the severity of mitral valve narrowing. However, murmur may diminish in intensity as the stenosis increases. Pericarditis and cardiac tamponade are clinical problems that involve the potential space surrounding the heart or pericardium. Pericarditis is one cause of fluid accumulation in this potential space; cardiac tamponade is the hemodynamic result of fluid accumulation. Pericardial friction rub is best heard at the lower left sternal border or apex when the patient is positioned sitting forward or on hands and knees. A friction rub may be distinguished from a cardiac murmur by its changing character from heartbeat to heartbeat and patient position changes [7]. Pulmonic stenosis refers to a dynamic or fixed anatomic obstruction to flow from the right ventricle (RV) to the pulmonary arterial vasculature. Although most commonly diagnosed and treated in the pediatric population, individuals with complex congenital heart disease and more severe forms of isolated PS are surviving into adulthood and require ongoing assessment and cardiovascular care. Functional or physiologic peripheral pulmonary stenosis is a common cause of a systolic murmur in infants. The murmur of peripheral pulmonary stenosis may be continuous, softer, and higher pitched [7].

For majority of murmurs, as can be seen in Fig. 1, the morphology of murmur is different from actual heart sound and therefore, it is expected that an effective subspace separation technique is the best solution for this problem.

In this paper a new robust and adaptive approach based on subspace analysis using SSA for detection of murmur is suggested. This stems from the fact that in usual cases the subspaces of heart sound and murmur are distinct and separable. SSA as a powerful technique in time series analysis and signal processing has been introduced and applied to many practical problems. Here a constrained SSA with adaptive selection of subspaces has been introduced to extract the murmur signal. SSA incorporates the elements of classical time series analysis, linear algebra, multivariate statistics, multi-variate geometry, dynamical systems and signal processing [8]. This approach overcomes many limitations such as nonlinearity and nonstationarity of the signals. Moreover, contrary to the traditional methods of time series analysis and signal processing, the basic SSA method is non-parametric and does not require any prior assumption about the data. Furthermore, SSA decomposes a series into its component parts, while excluding the random (noise) component which is very important for the murmur extraction. Of the main feature of the proposed technique is that the extraction of murmur signal is achieved through successive extraction (or filtering) in an algebraically orthogonal projection. It also exploits the statistical differences between the two components in definition of a proper constraint. The rest of the paper is organized as follows: In Section 2 the Basic SSA is described, Section 3 introduces the proposed constrained adaptive SSA, the proposed algorithm for murmur extraction and empirical results are represented in Section 4, and finally Section 5 is devoted to summary and conclusions.

2. Singular spectrum analysis

The basic SSA method consists of two complementary stages: decomposition and reconstruction; each stage includes two separate stages. In the first stage the observed signal (often called time series) is decomposed and in the second stage the original source signal is reconstructed and used for further analysis. The main concept in studying the properties of SSA is *separability*, which characterizes how well different components can be separated from each other. The absence of approximate separability is often observed in series with complex structure. For