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Optimum heart sound signal selection based on the cyclostationary property

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ABSTRACT

Noise often appears in parts of heart sound recordings, which may be much longer than those necessary for subsequent automated analysis. Thus, human intervention is needed to select the heart sound signal with the best quality or the least noise. This paper presents an automatic scheme for optimum sequence selection to avoid such human intervention. A quality index, which is based on finding that sequences with less random noise contamination have a greater degree of periodicity, is defined on the basis of the cyclostationary property of heart beat events. The quality score indicates the overall quality of a sequence. No manual intervention is needed in the process of subsequence selection, thereby making this scheme useful in automatic analysis of heart sound signals.

1. Introduction

Computer-based analysis of digital heart sound signals has received wide attention in recent years. For example, many envelope extraction methods have been developed [1,2], envelope-based parameters have even been defined for in-home heart disorder monitoring [3,4], and an automatic detection method based on homomorphic envelogram was proposed by Gill et al. to detect heart sounds [13]. In addition, time–frequency techniques have also been applied to the analysis of heart sounds [5–7]. Over the last 3 years, heart sounds have also been proposed for use as a biometric for human identification [8–10]. However, in practice, recordings may be longer than necessary, as algorithms only require a particular subsequence. In addition, some parts of the recording may be contaminated by interference, noise, spikes, etc. These contaminated parts should be pruned away before further analysis, and human intervention is often needed to select the subsequence with the best quality. Thus, it is of interest to develop techniques to automatically select the subsequence with the best quality. However, this leads to a practical question: what is a suitable criterion for evaluating the quality of a subsequence?

To the best of our knowledge, Beritelli and Spadaccini [8] were the first to propose a quality index, which was based on the cepstral distance between homogeneous cardiac sounds, to gauge the quality of recordings of heart sounds (first and second heart sounds, S1 and S2, respectively). They defined the reciprocal of the cepstral distance as the quality score, based on the reasoning that the greater the quality score was, the higher the degree of consistency was in the continuous heart sounds. They concluded that continuous heart sounds with the maximum quality score have the best quality. This quality index performed very well, as illustrated in their paper. However, we noted that their scheme requires a preprocessing step, i.e., segmentation of the heart sound signals, which is often inaccurate. Thus, manual segmentation is needed to improve accuracy, making their scheme only partially automatic in this sense. Moreover, we noted that a sequence of a heart sound signal will contain not only heart sounds (S1, S2, S3, and S4) but also murmurs. However, their quality index only takes S1 and S2 into account.

To realize complete automation, this paper proposes an optimum heart sound selection scheme that exploits the cyclostationary nature of heartbeats. That is, heart sound signals are, in general, highly periodic, but interference and noise are random. The degree of periodicity of a recording is thus related to the overall quality of the heart sound signal, which is used here as a quality score to evaluate heart sound sequences. This score reflects the overall quality of a sequence, including heart sounds and murmurs (if any). In addition, no heart sound segmentation is required, which means the scheme is completely automatic.

The paper is organized as follows. Section 2 introduces the cyclostationary property of heart sounds and the definition of quality index. In Section 3, we propose a time-varying quality index which is used in continuous heart sound data. Some experiments and discussions are shown in Section 4. Finally, conclusion is given in Section 5.

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2. Quality index

2.1. Definition of cyclostationarity for heart sound signal

It is known that heart sounds are generated by heart valve closure, blood flow, and cardiac muscle contractions. These events are repeated in each cardiac cycle. Furthermore, the heart rate does not change abruptly in a short time. As such, it is safe to assume that heart sound signals are quasi-cyclostationary [11,12]. Let $x(t)$ be a digital heart sound signal sequence. In extreme cases, the cycle duration T is constant. The time-varying autocorrelation is given as

$$R_x(t,\tau) \triangleq \lim_{N\to\infty} \frac{1}{2N+1} \sum_{n=-N}^{N} x(t+\tau/2+nT)x^*(t-\tau/2+nT) \quad (1)$$

$R_x(t,\tau)$ is a periodic function, i.e., $R_x(t,\tau) = R_x(t+T,\tau)$. We expand $R_x(t,\tau)$ using the Fourier series as

$$R_x(t,\tau) = \sum_{m=-\infty}^{+\infty} R_x(m/T,\tau)e^{j\,2\pi\, m\, t/T} \quad (2)$$

where m is a real number and m/T is called the cycle frequency, denoted as α. Eq. (2) becomes

$$R_x(t,\tau) = \sum_{\alpha=-\infty}^{+\infty} R_x(\alpha,\,\tau)e^{j2\pi\alpha t} \quad (3)$$

The coefficient of the Fourier series is given as

$$R_x(\alpha,\,\tau) = \langle x(t+\tau/2)x^*(t-\tau/2)e^{-j2\pi\,\alpha\,t}\rangle_t \quad (4)$$

where the operator $\langle\cdot\rangle_t$ denotes the time average. $R_x(\alpha,\tau)$ is called the cyclic correlation function, which degenerates into a traditional correlation when the cycle frequency α is zero. In the extreme case, the basic cycle frequency of the heart sound signal is $\alpha=1/T$. $R_x(\alpha,\tau)\neq 0$ only if cycle frequency is $k\alpha$ and $R_x(\alpha,\tau)=0$ elsewhere, where k is an integer. However, the cycle duration of a normal heart sound signal is not fixed; it varies with time. This is known as heart rate variability (HRV). Thus, $R_x(\alpha,\tau)\neq 0$ even if α is any real number. $R_x(\alpha,\tau)$ can be transformed into the frequency domain via the Fourier transform. That is

$$S_x(\alpha,f) = \int_{-\infty}^{\infty} R_x(\alpha,\tau)e^{-j2\pi\,f\,\tau}\,d\tau. \quad (5)$$

$S_x(\alpha,f)$ is referred to as the cyclic spectral density. In any stochastic process for which $R_x(\alpha,\tau)\neq 0$ or $S_x(\alpha,f)\neq 0$, the process exhibits a certain degree of cyclostationarity at cycle frequency α. In this paper, the analysis in the cycle frequency domain is of primary interest. We can get the cycle frequency spectral density (CFSD) using the integral

$$\gamma_x(\alpha) = \int_{-\infty}^{\infty} |S_x^{\alpha}(f)|\,df. \quad (6)$$

The relative rate defines the quality index for a heart sound signal

$$d(\eta) = \frac{\gamma_x(\eta)}{\int_0^{\beta}\gamma_x(\alpha)d\alpha} \quad (7)$$

where β is the maximum cycle frequency considered and η is the basic cycle frequency indicated by the first peak location of $\gamma_x(\alpha)$. Noise and interference distort the heart sound signal, thus degrading the cyclostationarity. It is therefore reasonable to conclude that a heart sound sequence with less noise and interference will have high degree of periodicity and thus high quality. The quality index thus has the ability to act as a quality score for heart sound signals.

2.2. Data acquisition

A heart sound signal was recorded at the authors' laboratory from a normal subject. The subject (male, aged 33) lay on his back on an examination bed and was kept under stable conditions. A sensor was placed on mitral site. ECG and heart sounds were recorded synchronously. The bandwidth of heart sounds is about 500 Hz. Thus, the sampling rate is set to 2 kHz, sufficient to meet the requirements of Nyquist's sampling theorem. The aural environment in the lab was controlled to allow recording to be low-noise heart sounds.

2.3. Examples of quality index calculation

A heart sound signal lasting 6 s is shown in Fig. 1(a). The CFSD of the signal at α from 0 to 1.5 Hz is given in Fig. 1(b). It can be seen that the signal has only one basic cycle frequency, as indicated by the first peak location at 1.02 Hz. The quality index is calculated according to (7). We get d (1.02)=2.07. The signal quality degrades if the signal is contaminated by interference and noise. For example, the signal contaminated by simulated interference and noise is shown in Fig. 2(a). The interferences are indicated by the ellipses, which has the same frequency band as that of the heart sounds. The CFSD is given in Fig. 2(b). It is found that the peak still occurs at 1.02 Hz, but the quality index at this cycle frequency

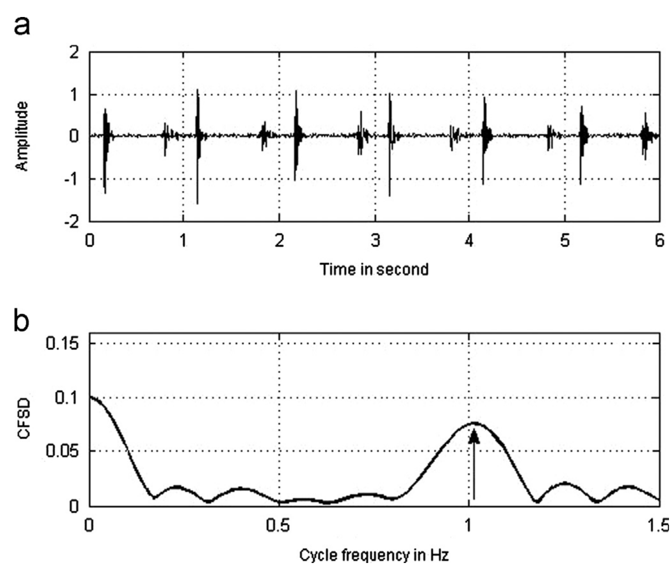

Fig. 1. CFSD calculation of a normal heart sound signal: (a) A normal heart sound signal. (b) CFSD of the normal signal. The quality score of the signal is 2.07.

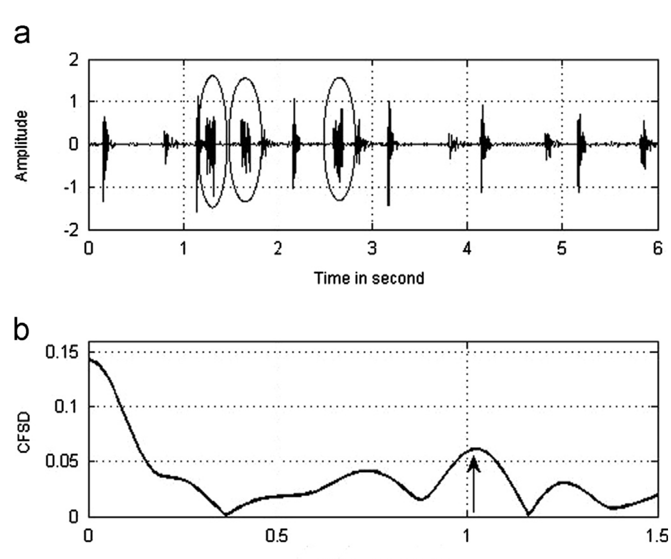

Fig. 2. CFSD calculation of a contaminated normal heart sound signal: (a) A normal signal was contaminated with simulated interference and noise. (b) CFSD of the contaminated signal. The quality score is 1.44.