Computer-Aided Analysis and Classification of Heart Sounds Based on Neural Networks and Time Analysis

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ABSTRACT

This paper describes a Computer-aided Heart sound Analysis and Classification System (CHACS)[1] based on neural networks and time analysis. In this system, two subsystems in both time and frequency domains are proposed. In the first subsystem, a multi-layer perceptron neural network is adopted to classify heart sound patterns. In the second subsystem, a set of heuristic rules is used to characterize heart sounds. The individual classification results of these two subsystems are combined to give the final suggestion. Using this system, heart sounds can be selectively stored, retrieved, enhanced, and replayed. Besides, CHACS provides an on-line display of the heart beat rate and allows an objective and reliable classification of heart sounds. Experimental results show that a classification rate of 95.6% is obtained.

1. INTRODUCTION

In past years, although the ever increasing sophistication and number of diagnostic methods in cardiology, e.g., ultrasound and electrocardiogram, have added much to our understanding of the action of the heart in health and disease. Cardiac auscultation remains basic to the examination of the heart. The most commonly auscultated heart sounds can be divided into (1) normal sounds (the first (S1) and second (S2) heart sounds), (2) abnormal variations of S1 and S2, (3) sounds that may be "physiologic" or "pathologic" (S3 and S4), and (4) sounds that usually reflect cardiac disease such as ejection sounds or clicks (ES), mid- or late-systolic clicks (MSC) and opening snaps (OS) [1].

During auscultation of the heart, we perceive air-transmitted sounds through the stethoscope. At the present time, auscultation of the heart is limited by four factors. First is the threshold sensitivity of the human ear. The normal adult can detect sound from 20 to 14,000 cycle per second (cps). Below 1000 cps there is a progressive decrease in auditory sensitivity. Almost all clinically significant cardiovascular sound occurs in the frequency range of 20 to 500 cps. Thus, an intense cardiovascular sound may be perceived as a softer sound and be more difficult to hear. The second limiting factor is the stethoscope itself. The bell or diaphragm of a stethoscope selectively transmits low- or high-frequencies, respectively. Appropriate use of the bell or diaphragm is critical to accurate auscultation [1]. The third limiting factor is that only single channel cardiac auscultation is allowed at a time. Essentially, there are four principle areas in cardiac auscultation. However, we cannot ausculate heart sounds at four areas simultaneously. The fourth limiting factor is that there are no objective and reliable methods for the classification of heart sounds.

In recent years, several approaches to the classification of heart sounds have been presented[2]-[4]. Most of them have been emphasized on the techniques of pattern recognition in frequency domain. However, when a sufficient amount of training patterns is not available, the classification performance of the system will degrade dramatically. In this paper, in order to deal with some of above limitations, a new computer-aided heart sound analysis and classification system (CHACS), based on neural networks in frequency domain and the onset time of heart sounds in time domain, is constructed to help doctor in clinical cardiac auscultation. Using this system, heart sounds can be selectively stored, retrieved, enhanced, and replayed. Besides, CHACS provides an on-line display of heart beat rate and allows an objective and reliable classification of heart sounds.

2. SYSTEM DESCRIPTION

CHACS consists of an IBM personal computer, a custom-built analog-to-digital converter (ADC), and a stethoscope coupled with a unidirectional microphone. In CHACS, two subsystems are constructed for heart sound classification in order to take into consideration the information in both time and frequency domains. The individual results of these two subsystems are combined to give the final classification result.

[1]This work was supported by the National Science Council of the Republic of China under Grant NSC82-0420-E006-084

0-7803-2431-5/95 $4.00 © 1995 IEEE

2.1 Subsystem in frequency domain

The block diagram of the frequency-domain subsystem is shown in Fig.1. In this subsystem, the heart sound signal is treated as the speech signal. The underlying assumption in most speech signal processing schemes is that the properties of the speech signal change slowly with time. This assumption leads to a short-time processing method in which short segments of the heart sound signal are isolated and processed. Therefore, a 2-second rectangular window is applied to the heart sound signal. These short segments, which are sometimes called analysis frames, overlap one another. The spectrum of each analysis frame, calculated by Fast Fourier Transform (FFT), is used as the input feature vector. This subsystem is composed of a heart sound candidate selector and a neural network classifier. The heart sound candidate selector is used to screen out unreasonable heart sound candidates in order to accelerate the classification speed. The neural network classifier is then used to decide the classification result. In the heart sound candidate selector, the training heart sound feature vectors are clustered into a set of K codebook vectors using the K-means algorithm [7]. For each heart sound, a membership table is established, which records all the codebook vectors belonging to this heart sound. For each input vector, the nearest codebook vector is decided and used to determine its corresponding heart sounds according to the membership table. Then the scores for all the corresponding heart sounds are incremented by one. Finally, heart sounds with ten most promising scores are chosen as the heart sound candidates. As a result, only these heart sound candidates are taken into account for further classification. Thereafter, a multi-layer perceptron neural network [5], having been proven useful in pattern recognition, is adopted to classify heart sound patterns. Finally, the five most promising heart sounds are used for further decision.

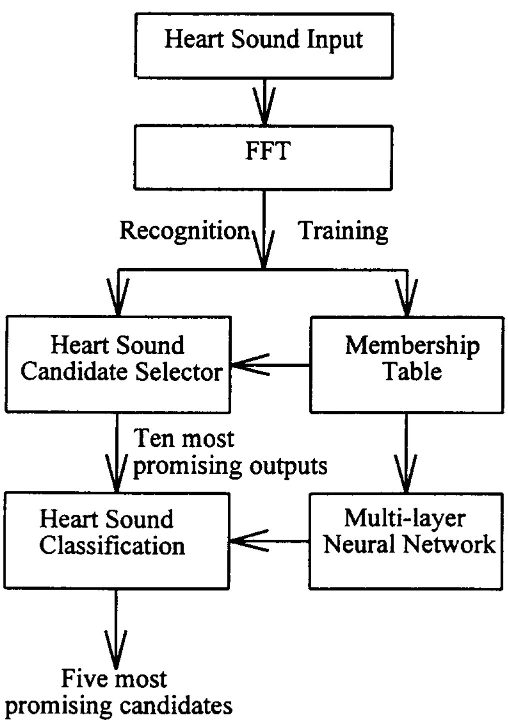

Fig. 1 Block diagram of the frequency-domain subsystem

2.2 Subsystem in time domain

The block diagram of the time-domain subsystem is shown in Fig.2. In this subsystem, since the heart sound signal is a quasi-periodic signal, the short-time autocorrelation function [6] and the short-time energy function are used as the characteristics to determine the period of the heart sound signal. A type I Chebyshev IIR bandpass filter is used to enhance the heart sound signal in the frequency range of 20 to 500 cps and to suppress extraneous noise. The short-time autocorrelation function is defined as [6]

$$R_n(k) = \sum_{m=-\infty}^{\infty} s(m)w(n-m)s(m+k)w(n-k-m) \quad (1)$$

where $R_n(k)$ is the k-th autocorrelation "lag," s(m) is the heart sound signal, and w(n) is a 2-second rectangular window function. The short-time energy function is defined as

$$En = \sum_{m=-\infty}^{\infty} s(m)w(n-m) \quad (2)$$

In clinical auscultation, the onset time difference between systolic heart sound and S1 and that between distolic heart sound and S2 are two kinds of important information. According to our investigation, the silence interval before S1 is longer than that before other heart sounds and the energy of S3 or S4 is much lower than that of S1. Driven by this property, in each period of the heart sound signal, the onset time of S1 can be determined based on the silence interval. Once the onset time of S1 has been determined, other heart sounds can be characterized according to the onset time difference between heart sounds and the reference heart sound S1 or S2, listed in Table I. Finally, the five most promising heart sounds are selected and combined with the candidate outputs of the frequency-domain subsystem to give the final result.

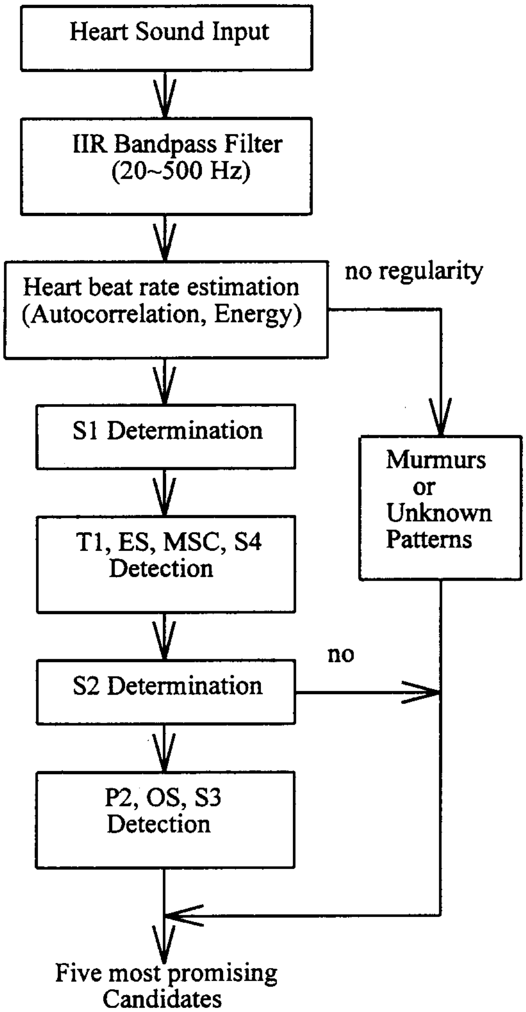

Fig.2. Block diagram of the time-domain subsystem

3. EXPERIMENTS

The training and test heart sound patterns used in CHACS were provided by National Cheng Kung University Hospital, Tainan, Taiwan, R.O.C.. Thirty-two patients with heart disease and forty-six normal people were asked to provide a 15-second recording of heart sounds in a silent environment. Heart sound signals were digitized by a 12-bit ADC at a 8KHz sampling rate. A 2-second rectangular window was used to compute FFT, short-time autocorrelation and short-time energy. In frequency-domain subsystem, half of the heart sounds were used as the training patterns, and all the heart sounds were used as test patterns. The experimental results are shown in Table II. From this table, a classification rate of 95.6% for CHACS is obtained with 93.3% for the frequency-domain subsystem and 91.8% for the time-domain subsystem. The combination of these two subsystems improves the classification rate from 93.3 % (or 91.8%) to 95.6%. This result demonstrates that these two subsystems complement each other. In addition, the classification rate of reference heart sound S1 or S2 is higher than that of other heart sounds. This is due to the fact that the properties of S1 and S2 are more obvious and easy to detect than that of other heart sounds. Therefore S1 and S2 are used as the reference heart sounds. The performance of the time-domain subsystem is superior to that of the frequency-domain subsystem. This is because insufficient training patterns were used in frequency-domain subsystem. While the time-domain subsystem, using rules based on doctor's auscultation experience, achieves higher performance as long as reference heart sounds S1 and S2 are correctly determined.

Table I The onset time difference with respect to reference heart sound S1 or S2

Heart sounds	Reference heart sound	Onset time difference (second)
S4	S1	-0.4~-0.00
T1	S1	0.00~0.04
ES	S1	0.04~0.10
MSC	S1	0.14~0.30
S2	S1	0.30~0.50
P2	S2	0.00~0.08
OS	S2	0.04~0.12
S3	S2	0.12~0.2

4. DISCUSSION

Suitable computer-aided heart sound analysis and classification systems have been difficult to develop. This study is one of the first to report the clinical use of a reliable heart sound analysis and classification system. We use two subsystems in both time and frequency domains to identify the acoustic patterns of heart sounds. The subsystem based on neural networks in frequency domain needs a sufficient amount of training patterns, while the subsystem in time domain needs no training patterns. On the other hand, the subsystem in time domain is easily affected by noise, while the subsystem in frequency domain is not so sensitive to noise. Evidently, these two subsystems complement each other. As a result, CHACS achieves a high performance. By the way, CHACS has been used for clinical cardiac auscultation at National Cheng Kung University Hospital.

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Table II Average heart sound classification rates for three classification systems

Heart sounds	Subsystem in frequency domain (%)	Subsystem in time domain (%)	CHACS (%)
S1	98.7	99.5	99.5
S4	89.3	92.1	94.5
T1	88.5	90.3	93.8
ES	86.4	88.6	92.6
MSC	87.5	89.8	94.0
S2	98.1	98.9	98.9
P2	91.4	93.2	95.8
OS	91.5	91.8	94.2
S3	95.1	96.0	97.3
Average	91.8	93.3	95.6