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To cite this article: Yujia Lu et al 2019 J. Phys.: Conf. Ser. 1168 022038

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A Heart Rate Calculation Method Based on Dynamic Rectangular Window Interception

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Abstract. Aiming at the detection of instantaneous heart rate of heart sounds, a dynamic rectangle window interception calculation method was designed and a heart sound acquisition system was developed. The system can be used to monitor the state of heart at home for adults and foetuses. The algorithm can be used for analysis of adult heart sounds, fetal heart sounds acquired by the acquisition system and ultrasound Doppler heart sound. The algorithm firstly performs a normalization processing on the sound signal and then filters the filter, captures the data in a rectangular frame dynamically, locates the heart sound signal, calculates the instantaneous heart rate, and finally obtains the heart rate with high accuracy. Study shows that the heart rate algorithm has the characteristics of high recognition accuracy and fast calculation speed, which can realize the convenient and rapid home heart rate monitoring for adults and fetuses.

1. Introduction

According to the statistics of heart disease and stroke from American Heart Association (AHA) in 2016, heart disease has become the first killer of global population health. In 2013, 31% of deaths were caused by cardiovascular disease and 11.8% were caused by stroke [1]. In recent years, the incidence of heart disease and mortality in developed countries has dropped significantly due to the early prevention. Long-term real-time monitoring and diagnosis of heart conditions may lead to the acquisition of pathological information before a sudden heart attack. Real-time monitoring of heart rate is one of the important indicators for cardiac condition monitoring. In addition, for pregnant women, fetal heart rate is also an important indicator to determine the health of the fetus.

At present, the monitoring of adult heart rate is generally performed by using a common stethoscope for monitoring and counting or by using a wearable device such as a smart bracelet based on pulse pulsation, and the method is relatively simple. However, the fetal heart rate monitoring is relatively complicated. The fetal heart sound is relatively weak, and then transmitted to the outside through the amniotic fluid. At the same time, it is mixed with other noises in the body. With unskilled medical personnel directly monitoring with a stethoscope, the diagnosis will be difficult.

Currently, the most important method for fetal heart rate detection is based on Doppler technology. However, studies have shown that when using ultrasound to detect fetal heart sound signals, it may stimulate the fetus and cause certain damage to the fetus [2]. Therefore, how to obtain the original fetal heart sound by passive auscultation method and calculate the instantaneous fetal heart rate with higher accuracy has become a research problem. The method proposed by Ari and Dokur et al. [3-5] is...
to use a rectangular window with an average heart rate or a certain length as a reference signal, but in general the average heart rate is unknown. In response to these problems, this paper proposes an algorithm that can be used for analysis of adult heart sounds, fetal heart sounds and Doppler fetal heart sounds, and provides methodological support for heart rate acquisition in many situations.

2. Data collection

There are three main types of data obtained in this paper, including adult heart sounds, fetal heart sounds collected by the acquisition system, and ultrasound Doppler heart sound collected from the hospital. The sample data in the experiment is further processed as a relatively stable segment from the acquired data. The specific data amount and data type are shown in Table 1.

| Data Sources                      | Signal length / s | type of data | Sampling rate / Hz |
|----------------------------------|-------------------|--------------|--------------------|
| Auscultation collection system    | 20~100            | .wav         | 8000               |
| Adult heart sound                |                   |              |                    |
| Fetal heart sound                | 20~100            | .wav         | 8000               |
| Ultrasound Doppler fetal heart sound | 20~100          | .mp3         | 500                |

3. Heart sound characteristic analysis

3.1 Heart Sound Generation And Influencing Factors

The generation of heart sounds is related to mechanical vibration caused by myocardial contraction, valve opening and closing, and blood flow impact in the cardiac cycle.

Vibration can be transmitted to the chest wall through the surrounding tissue, and the heart sound can be heard in a certain part of the chest wall with a stethoscope[7]. The normal heart sound signal includes a first heart sound (S1), a second heart sound (S2), a third heart sound (S3), and a fourth heart sound (S4). In the case of abnormality, in addition to these four heart sound components, heart murmurs, heart sound splits and additional sounds may occur. In general, only the first heart sound and the second heart sound can be detected. The first heart sound occurs during the systole phase, and the second heart sound occurs during the diastolic phase. The information contained in the first heart sound and the second heart sound plays an important role in cardiac auscultation. Our research is mainly in the first and second heart sounds.

The heart sound signal obtained by the auscultation system is worse than the heart sound signal acquired by the ultrasound Doppler. The hospital uses ultrasound Doppler diagnostic instrument to obtain heart sound signals. Ultrasound Doppler diagnostic instrument uses ultrasonic non-cluster continuous wave Doppler principle, which consists of ultrasonic transducer and circuit part that is acoustically coupled with the mother's abdomen. An ultrasound beam reflected from a moving structure (such as a heart valve) or a collection of scatterers (such as a red blood cell population in a blood vessel) detects the Doppler shift therein, obtains information on the velocity of the target, and is then monitored by the human ear. The instrument analysis uses images to display or uses images to visualize the motion of internal organs of the human body.

Both the auscultation system and the ultrasound Doppler diagnostic instrument can detect heart sound signals, but the principles of the two are different. The strength and quality of the acquired heart sound signals are also very different. However, the ultrasound Doppler diagnostic apparatus needs to apply a couplant on the pregnant woman’s belly before the test, and the US Food and Drug Administration has published an article stating that the use of the ultrasonic detector is a prescription-level operation and needs to be performed by a medical professional in the hospital. Stethoscopes do not have this limitation, and they are easy to carry and have the advantages of home and self-diagnosis.

The stethoscope has a high requirement for the heart sound signal. When the fetal heart sound signal is heard, the heart sound signal generated by the fetal heart beat propagates through a
complicated environment due to the fetal in the mother's uterus, and the signal is subject to many disturbances and attenuation. In the mother's abdomen, when using the acoustic sensor to collect fetal heart sounds, the collected acoustic signals are in addition to the fetal heart sounds, as well as maternal heart sounds, internal noise (including maternal breath sounds, fetal movement noise, maternal intestinal percussion, blood flow sounds, and other Organ noise, etc.), external noise (including sensor jitter noise, current sound, and environmental noise) [8]. As shown in Figure 1.

![Figure 1. Fetal heart sound propagation path and noise source.](image)

3.2 Analysis of different categories of heart sound characteristics

The heart sound data obtained by the heart sound auscultation system is 8000 Hz with the data range of [-1, 1], and the collected adult heart sound data is shown in the following figure 2. The collected fetal heart sound data is shown in Figure 3. The heart sound signal of the fetus using Ultrasound Doppler is shown in Figure 4. From the figures, it can be seen that the adult heart sound signal obtained by the auscultation sound clearly distinguishes the S1 and S2 heart sounds. Although there are a lot of noises mixed, the main components are easy to distinguish. The fetal heart sounds acquired by the auscultation system are mixed with little environmental noise and no strong fetal movement. Fetal heart sound signal using ultrasound Doppler has a relatively clear S1, S2 sound, and there is also a certain noise interference.

![Figure 2. Adult heart sound signal acquired by the acquisition system.](image)

![Figure 3. Fetal heart sound signal acquired by the acquisition system.](image)

4. Heart rate detection method

The heart sound signal was collected in a relatively quiet environment. However, the fetal heart sound original signal is a mixed signal of the fetal heart sound signal and the noise signal, and the signal to noise ratio is relatively low. The fetal heart sound original signal acquired by ultrasound Doppler is also a mixed signal and needs to be processed.

The instantaneous heart rate detection method, enhanced in the short-time Fourier rectangular window, can acquire more signal knowledge in the window. The current research mainly focuses on the preprocessing of the original signal, and the independent component analysis (ICA), blind separation and other methods for signal separation. The rectangular window dynamic ingestion method can make the peak detection highly robust with low signal purity and noise-to-noise ratio. The important is to obtain the position of the heart sound signal point.
The heart sound extraction process and the detection of instantaneous heart rate need to normalize the original signal first, then filter the interference signal, and use the rectangular frame threshold to detect the effective peak value, thereby obtaining the instantaneous heart rate of the heart sound signal.

According to the above principle, the processing flow chart of the heart sound signal is shown in Figure 5.

4.1 Data normalization
Data normalization is a non-dimensional processing method that changes the physical value into a relative value with a certain relative relationship, and reduces the difference between the magnitudes. It operates on the data represented by the matrix, and compensates for the effects of mismatch by normalizing the statistical properties of the feature vector, the cumulative density function, etc. The main purpose is to eliminate the difference between the properties and smooth the wave function of the data sample values.

This paper uses the linear normalization method with the raw data linearly transformed to the resulting value from 0 to 255. The conversion function is:

\[
X' = \frac{X - \text{min}}{\text{max} - \text{min}}
\]  

Where max is the maximum value of the sample data, min is the minimum value of the sample data.

4.2 Filter processing
The Butterworth filter is a low-pass filter with the largest flat-amplitude response [9], which has the advantage of balancing the characteristics in terms of linear phase, attenuation slope and loading characteristics, and is the first choice for processing raw data.

The squared amplitude response of the Butterworth low-pass filter is like equation 2:

\[
| H_a(j\Omega) |^2 = \frac{1}{\sqrt{1+(\Omega/\Omega_c)^{2N}}}^2
\]  

Where N is the order of the filter, \(\Omega_c\) is the cutoff frequency [10]. In this experiment, the cutoff frequency is 500 Hz and the calculating order is 1.

The filtered curve function by Butterworth low-pass filter is shown in Figure 6.

4.3 Instantaneous heart rate extraction algorithm
There are three main steps in calculating the instantaneous heart rate, including: (1) dynamic rectangular window for dynamic input data; (2) calculating the maximum value of the data in the window and verifying whether the maximum value is valid; (3) obtaining a valid maximum value and recording the time of the value, the instantaneous heart rate is calculated using equations described above.
4.3.1 Dynamic rectangular window for dynamic input data: According to the statistics, the normal fetal heart rate is between 120 to 160 beats per minute with less than 120 times or more than 160 times, considered as abnormal heart rate. The normal range of adult heart rate is 40 to 100 beats per minute. If the abnormal heart rate does not exceed 10 seconds in the abnormal range, it is also defined as normal heart sound. So we can divide the length of the rectangular window between the normal and the abnormal range for the expected heart rate.

Taking the adult heart sound as an example, the sampling rate of the sound capturing device is 8000 Hz, that is to say 8000 sampling points per second. We suppose that the lower limit of the heart rate is tolerance range to 40 times and the upper limit to 100 times. The length of the rectangular window is:

\[ \text{_max} / (40 / 60) \times \text{Fs} = (3) \]

\[ \text{_min} / (100 / 60) \times \text{Fs} = (4) \]

Where \(_\text{max}\) is the length of the rectangular window with the largest fault tolerance range. If the heart rate point falls on both ends of \(_\text{max}\), the heart rate is 40. Similarly, \(_\text{min}\) is the length of the rectangular window with the smallest tolerance range. When the heart rate point falls on \(_\text{min}\), the heart rate is 100. Fs is the sampling rate with value of 8000 Hz.

4.3.2 Algorithm principle: The maximum value of the data within the length of the rectangular window is firstly calculated. It should be verified that the obtained maximum value is within a reasonable heartbeat period. If the distance between the point where the maximum value is obtained and the previous maximum value is less than \(_\text{min}\), the obtained maximum value is interference data and should be discarded. Another maximum value within the length of the rectangular window is now compared.

The algorithm steps are as follows:

Step 1. Calculating the size of the corresponding rectangular window according to the data type;
Step 2. Finding the maximum value of the data in the rectangular window, and recording the time and position of the maximum value;
Step 3. Comparing the position of the maximum value with the position of the previous maximum value. If the distance is less than \(_\text{min}\), the algorithm will set the maximum value to 0 and repeat Step 2, Step 3 to calculate the effective maximum value.
Step 4. Moving the rectangular window forward and repeat Step 2, Step 3 until the window contains the last data.
Step 5. Calculating the instantaneous heart rate based on the time of the saved maximum value. The instantaneous heart rate calculation formula is as follows:

\[ R = \frac{60}{t} \] (5)

Where R is instantaneous heart rate per minute and t is the time interval between two adjacent maximum values.

5. Experiment Analysis
The heart rate detection algorithm proposed in this paper is programmed with MATLAB R2016b. The adult heart sound signal used in the experiment was collected by the heart sound collection system introduced above. The fetal heart sound signal is composed of two parts, which are respectively collected by the heart sound collection system and the hospital ultrasound Doppler fetal heart rate meter. The sampling frequency of the heart sound collection system in this paper is 8000 Hz, and the sampling frequency of the hospital Doppler is 500 Hz.
5.1 signal processing
The collected signals are first normalized and then low-pass filtered to remove high frequency noise (Figure 6). After filtering with the filter, the signal with removing high-frequency noise can be obtained. Compared with the original data, the heartbeat amplitude fluctuation can be clearly seen on the figure 7, which helps the subsequent value-taking algorithm to obtain an accurate heartbeat point.

Figure 6. Heart sound data filtering.

Figure 7. Time domain waveform of filtered adult heart sound signal.

Figure 8. Time domain waveform of filtered poor original fetal heart sound signal.

Figure 9. Time-domain waveform of filtered ultrasound Doppler fetal heart sound signal.

Through Figures 8 and 9, it can be known that the poor original fetal heart sound is less effective because of more interference factors; The Doppler signal is clear, and a clear heartbeat cycle is known based on significant amplitude changes.

The heart sound signal is positioned in the pre-processed heart sound signal, and the data point is taken by the rectangular frame to find the best value algorithm to take the accurate heart sound signal. Following figures show the best positioning points which are used to calculate the sensitivity of this algorithm and the accuracy of the heart rate.

As shown in Figures 10, in the figure, the selected maximum value positions are marked and the positioning points are the color lines above the signal in the graph. The marked points are almost at the peak, and the positioning is accurate. In the aspect of adult heart sound, this algorithm has higher positioning accuracy.
Figure 10. Maximum value position of adult heart sound.

Figure 11. Maximum value position of fetal heart sound.

Figure 11, 12 are the heart sound positioning results of the fetal heart sound and the Ultrasound Doppler sound respectively. The fetal heart sound signal of the poor original signal can be found is unstable and uneven spacing. The signal positioning effect obtained by ultrasound Doppler is better than fetal heart signal.

Figure 12. Ultrasound Doppler fetal heart sound information signal positioning heart sound.

Figure 13. Instantaneous heart rate for adult heart sound.

Figure 14. Instantaneous heart rate for fetal heart.

Figure 15. Instantaneous heart rate for Ultrasound Doppler sound.

Equation 5 was used to calculate the instantaneous heart rate from the heart sound signal. The threshold value of the rectangular frame is \([ \_\text{min}, \_\text{max} ]\). For the adult heart sound, \_\text{min} is 60 and \_\text{max} is 100, For the fetal heart sound, \_\text{min} is 120 and \_\text{max} is 160. Accuracy calculation is the ratio of data in the normal range to the whole data. The calculated instantaneous heart rate of the adult fetus is shown in Figures 13, 14, and 15. Although there are abnormal heart rates in the pictures, they all have a very short time, which is a normal heart sound.
The average accuracy of the instantaneous heart rate of the three different signals were 95.74%, 96.09% and 81.54% respectively for adult heart rate, fetal heart rate and ultrasound Doppler fetal heart rate.

6. Conclusion

In this paper, a dynamic rectangular window interception calculation method is designed for different heart sound signals. The segmentation process is used to extract the heart sound signal points. Results show that the method has high positioning accuracy for the heart sound signal and the speed is fast in the process of calculation. According to the clinical verification experiments, the heart sound collection system designed is convenient and fast. The instantaneous heart rate value is quickly obtained. The method will be beneficial to the early diagnosis of the disease. Study shows that the instantaneous heart rate based on the heart sound is reliable. The heart sound collection process has higher requirements for the environment, and the data collected in the quiet environment is beneficial to the later data processing, and the acquired heart rate accuracy rate is relatively high. However, it is necessary to collect the original heart sound in a quiet environment. The accurate identification of heart sound in noisy environments and the determination of accurate heart disease in abnormal heart sounds will be the focus in the further research.

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