Passive Acoustic Maternal Abdominal Fetal Heart Rate Monitoring Using Wavelet Transform

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Abstract

We present a passive acoustic apparatus for maternal abdominal fetal heart rate (FHR) monitoring. The apparatus consists of an acoustic sensor module and a Laptop or a PDA embedded with signal processing algorithms. It is able to provide a calculated fetal heart rate instantaneously, real-time fetal heart sound waveform displays and audio playback. The fetal heart sound signals are detected, de-noised and reconstructed by utilizing wavelet transform based signal processing approach. The proposed approach improves the signal to noise ratio which allows reliable fetal heart rate variation to be estimated under very weak signal environment. The apparatus has gone through clinical trials in a local hospital on a sample group of 41 pregnant women.

1. Introduction

Monitoring the variations of fetal heart rate (FHR) is one of the most important approaches for fetal surveillance. Currently, fetal surveillance is performed mainly using ultrasonic based equipments such as ultrasonic Doppler fetal monitor and cardiotocography (CTG). However, frequent exposure to ultrasound radiation is not recommended for both fetus and mothers [1,2]. For that reason, maternal abdominal fetal electrocardiography (fECG) [6] and phonocardiography (fPCG) [1-5] are proposed as alternatives to the ultrasonic based approaches.

ECG and acoustic sensors are all passive in nature, and are suitable for long term monitoring. However, fPCG is more convenient as compared to fECG which requires proper placement of multiple electrodes. Moreover, fPCG is more like early age's auscultation that doctors used such approach to get the fetal information.

The majority of the early works on fPCG are in the area of sensor development [3-5]. More recent studies, on the other hand, concentrate on FHR estimation. Many of these methods, e.g., [7-11], could not deal with noisy fetal heart sound, except [2, 3] in which a series of carefully designed rules were proposed to enhance the robustness of the FHR calculation.

There is still a gap between the existing technologies and the user requirements for a safe, convenient and reliable fetal heart monitoring. Motivated by these needs, we conducted our study specifically on achieving a reliable FHR estimation under realistic situation and enhancing the fetal heart sound waveform display. The work was implemented on Laptop and HP PDA and had been tested on a group of 41 pregnant women in a local hospital.

The paper is organized as follows. In Section 2, the system and signal processing methodology are described. The experimental and clinical trail results are reported in Section 3. Finally we draw the conclusion in Section 4.

2. System description

The block diagram of the system is shown in figure 1. There are three modules, namely sensor, signal processing and output.

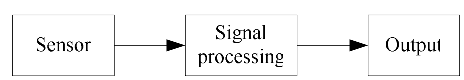

Figure 1. Block diagram of the system

2.1. Sensor module

The sensor module includes an acoustic sensor, a pre-amplifier, a low-pass filter, and an analogue to digital converter (ADC) which resides in the laptop or PDA. The analogue signal is connected to the Laptop or the PDA through their audio plugs.

The main components of the fetal heart sound fall in 35-110 Hz [1]. Thus, the sampling rate of 1 kHz is selected for the ADC and 500 Hz cut-off frequency for low-pass filter.

2.2. Signal processing module

Fetal heart sound is a very weak signal and is corrupted by various noises such as maternal organ sound, fetal and maternal movement effect, etc. To achieve reliable fetal heart rate estimation, the wavelet transform based signal processing approach is used. A detailed description of each signal processing module is given below.

A. 5 level wavelet decomposition

The fetal heart sound signal is interfered by various noises with unknown spectral and temporal characteristics. The wavelet decomposition is applied to decompose the corrupted signal into several levels. The purpose of the decomposition processing is to remove the decomposed level which seriously corrupted by noise so as to improve the signal-to-noise-ratio.

The 5 level Coiflet wavelet decomposition is used in the processing.

B. Autocorrelation analysis

Fetal heart sound can be roughly assumed as a periodic signal as it consists of two periodic pulses (S_1 and S_2). Although the intervals of the heart beat always varying slightly, it can be regarded as a fixed periodic signal in a short period.

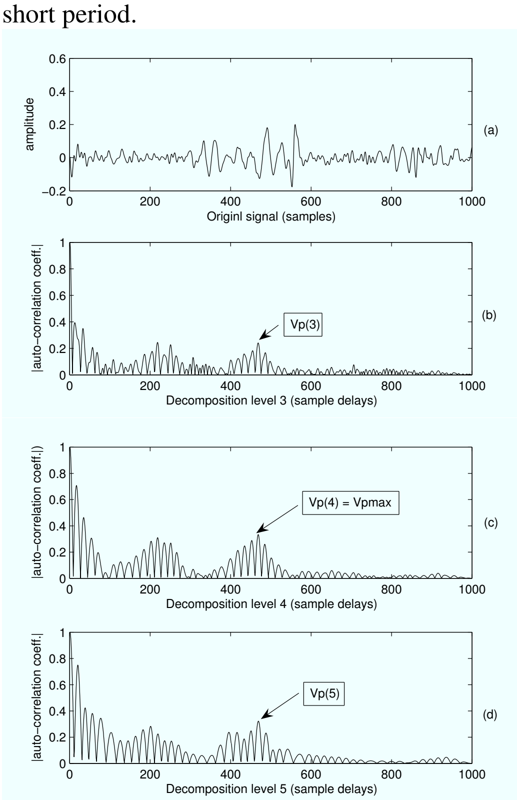

Figure 2. An example of 1 second autocorrelation function for decomposition signal

The periodic signal means similarity of a waveform with a time delayed version of itself. The auto-correlation function can be used to quantify this similarity. In order to examine how the signal is contaminated by non-periodic noise, the auto-correlation analysis for every decomposed level is done.

The autocorrelation function R at lag j for a discrete signal $\{S_n\}_{n=0}^{N-1}$ is

$$R(j) = \frac{\sum_{j=0}^{N-1} (S_{n+j} - \mu)(S_n - \mu)}{N\sigma^2}; \quad \text{for } j \in N; \qquad (1)$$

where μ and σ denote the mean and standard deviation of S_n respectively.

In our case, N=1000 is chosen as it corresponds to 1 second where more than two signal cycles exist during that time period [12].

Figure.2 shows an example of autocorrelation analysis of the signal. The original signal is illustrated in fig.2a, which is decomposed as 5 levels using wavelet transform. The magnitude of the autocorrelation coefficient of level 3, 4 and 5 are illustrated in fig.2b, 2c and 2d, respectively. The value of the peak Vp(i) for level i gives the information of the periodic signal corrupted by non-periodic noise. The peak from different decomposition level has different value which means that the signal quality corrupted by non-periodic noise is different. Therefore the autocorrelation analysis provides information required for signal reconstruction.

C. Fetal heart sound reconstruction

Based on the autocorrelation analysis in Section 2.2.B, the fetal heart sound is reconstructed. The rules of the signal reconstruction are defined as follows:

1) Find the maximum P point value:

$$Vpmax = \text{maximum}(V_P(i)); i = 1 \ldots 5$$

2) Generate reconstruction weighting coefficient as:

$$K(i) = \begin{cases} (V_p(i)/Vpmax)^2; & \text{when } V_p(i) \geq 0.8Vpmax \\ 0; & others \end{cases} \qquad (2)$$

3) Reconstruct the signal S_r as:

$$S_r = \sum_{i=1}^{5} K(i)S(i); \qquad (3)$$

where S(i) denotes the ith level decomposed signal.

Take figure.2 as an example, the level 4 has the maximum $\text{Vpmax} = 0.33$, then $K(4) = 1$; $Vp(5) = 0.32$, then $K(5) = 0.94$; $Vp(3) = 0.24$ and $K(3) = 0$.

D. Fetal heart rate (FHR) calculation

To estimate the fetal heart rate, the autocorrelation calculation is applied to reconstructed signal. The window length is 3000 samples based on the experimental data. Longer window is not recommended as the extraction quality of the periodic property decreases as window turns to be longer.

The peak detector [12] is used to find the cycle period. Since the 3000 samples may not cover the exact periodic cycles, the next 3000 signal samples will start from the position where autocorrelation coefficient peak corresponds to.

After peak detection, the time intervals of heart beat T(i) are calculated according to the peak positions and FHR can be estimated as:

$$FHR(i) = 60/T(i) \quad (4)$$

E. Performance evaluation

A MMI (Man-Machine-Interface) is vital for the user of the gadget so that the user can quantitatively evaluate the reliability of the estimated FHR.

We design a brief but effective performance evaluation factor employs auto-correlation of two neighbouring cycles of the signal. Suppose P indicates the first cycle peak, M_p is the mean of magnitude of autocorrelation of the cycle, the performance evaluation factor is:

$$PEF = Mp/P \quad (5)$$

Through our clinical trial data evaluation, we concluded that the value of the PEF corresponds to the situation on how the signal is contaminated by strong noise. Therefore it can be as an indicator to the reliability of FHR.

2.3. Output module

Two output functionalities are developed, namely visual and audio output modules.

Two modes can be selected for visual output module. Mode 1 is the waveform display of the reconstructed fetal heart sound which is more desired for the pregnant women self-monitoring. Mode 2 will display the variation of fetal heart rate for the doctors in clinical use as it provides clear information of foetus.

The audio output module is another important diagnostic tool for the doctor to check on the fetal heart beat rhythm. An experienced doctor can identify the S_1 and S_2 rhythm by listening to the fetal heart sound.

Human ears are insensitive to the low frequency band from about 100Hz downward [13]. Unfortunately most of fetal heart sound energy falls inside this frequency band. For that reason, in order to allow the user to listen to the heart beat rhythm more clearly and easily, the frequency shift method is realized. Based on the human ear sensitivity chart in [2, 3], when we shift the frequency to the high band such as by a 150Hz frequency shifting, the signal is acoustically amplified by about 20-40dB. At the same time, by using frequency shifting, we can effectively avoid the poor low frequency performance of the sound card of laptop (or PDA) and loudspeaker (or earphone).

The frequency shifting is implemented using the amplitude modulation [14] and high-pass filtering. The carrier wave frequency for amplitude modulation and cut-off frequency for high-pass filtering are both set at 150Hz.

2.4. Implementation

The design of the sensor module consists of a Teflon-made inverse corn with microphone embedded at its bottom. The pre-amplifier, low-pass filter and battery are all enclosed in the miniature box. The signal processing and display are realized using the laptop or PDA.

The user interface and the signal processing algorithm are programmed using VC++ for Laptop. The software can display the reconstructed signal waveform or display FHR in real time. Meanwhile, user can hear the reconstructed fetal heart sound through earphone or loudspeaker.

Limited signal processing methods is implemented in PDA due to its computation capability restriction. It is a simplifying version.

3. Experimental and clinical trail result

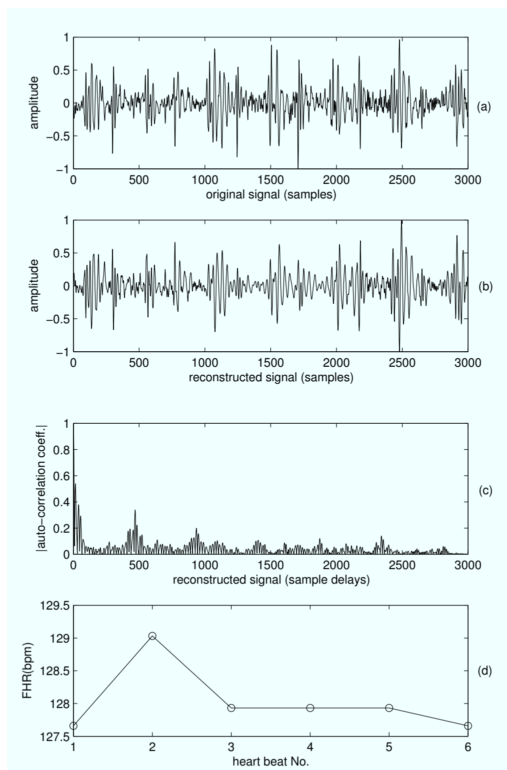

Figure 3. An experimental example

The clinical trials were carried out in a local hospital on 41 pregnant women who were in the 37^{th}-40^{th} pregnancy week. For each trial, a 10 minutes data was captured and processed.

Figure.3 shows an example of fetal heart signal enhancement and the resulting FHR estimation. The signal was recorded on the abdominal wall of a woman (66kg/162cm) with 38th pregnant week. Fig.3a is the original signal and 3b is the reconstructed signal. It is observed that after applying the proposed signal processing algorithm, the signal-to-noise-ratio is improved effectively. Fig.3c shows the autocorrelation coefficient of the reconstructed signal. Fig.3d is the instant fetal heart rate estimation, which is obtained from the peak detection of autocorrelation coefficient shown in 3c.

Table 1. Clinical trial results.

Clearness Grade	Number
5: very distinct	17
4: distinct	7
3: clear	7
2: need to listen attentively	6
1: cannot be heard at all	4

A subjective listening test was carried out by three subjects to evaluate the audible display performance. The processed signals are classified based on clearness into 5 grades. We observe that above 31/41 of the fetal heart sound has a clearness level of 3 and above, indicating that most of these signals are clear and distinctive.

In case where we could not hear the sound, we note that the pregnant women were very obese. This is not surprising as the CTG machine also experiences the same problem. Some other reasons may include the abnormal placenta position, unfavourable fetal position in the mother's womb and the movement of the fetus.

It is also observed that after applying the proposed processing, the non-periodic noise is reduced and the fetal heart signal is enhanced. Assisted by other signal processing methods the reliable FHR estimation is obtained. In most time, our device functions effectively and provides results close to the CTG records.

4. Conclusion

A passive acoustic maternal abdominal fetal heart rate monitor has been developed. The processed fetal heart sound can be easily identified by users. Reliable fetal heart rate variation can be obtained. Assisted by the performance evaluation factor, the reliability of the obtained FHR can be intuitively evaluated. On the other hand, we realize that comparing with the ultrasonic based medical equipments such as CTG, the performance of our system still needs to be improved. Therefore we suggest using the system as a supplementary tool rather than a substitution for the clinic applications.

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