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Extraction of fetal heart rate and fetal heart rate variability from mother's ECG signal

Khaldon Lweesy, Luay Fraiwan, Christoph Maier, and Hartmut Dickhaus

***Abstract*—**This paper describes a new method for extracting the fetal heart rate (fHR) and the fetal heart rate variability (fHRV) signal non-invasively using abdominal maternal electrocardiogram (mECG) recordings. The extraction is based on the fundamental frequency (Fourier's) theorem. The fundamental frequency of the mother's electrocardiogram signal ($f_{o\text{-}m}$) is calculated directly from the abdominal signal. The heart rate of the fetus is usually higher than that of the mother; as a result, the fundamental frequency of the fetal's electrocardiogram signal ($f_{o\text{-}f}$) is higher than that of the mother's ($f_{o\text{-}f} > f_{o\text{-}m}$). Notch filters to suppress mother's higher harmonics were designed; then a bandpass filter to target $f_{o\text{-}f}$ and reject $f_{o\text{-}m}$ is implemented. Although the bandpass filter will pass some other frequencies (harmonics), we have shown in this study that those harmonics are actually carried on $f_{o\text{-}f}$, and thus have no impact on the evaluation of the beat-to-beat changes (*RR* intervals). The oscillations of the time-domain extracted signal represent the *RR* intervals. We have also shown in this study that zero-to-zero evaluation of the periods is more accurate than the peak-to-peak evaluation. This method is evaluated both on simulated signals and on different abdominal recordings obtained at different gestational ages.

***Keywords*—**Aabdominal ECG, fetal heart rate variability, frequency harmonics, and fundamental frequency.

I. Introduction

FETAL heart rate variability (fHRV) is an important measure that can provide early information about fetal's wellbeing and identify those at risk of diseases such as sudden infant death syndrome (SIDS) [1] and supraventricular extrasystoles [2]. Previous studies of fHRV signals obtained using cardiotocography (CTG) have shown that fetal acidosis and fetal hypoxia are directly associated with reduced fHRV, which is directly related to increasing risk of perinatal mortality [3-6]. Currently, CTG is the main method by which fetal's wellbeing is monitored. However, fetal's beat-to-beat (*RR*) changes obtained using CTG are not accurate compared to those obtained from the electrocardiogram (ECG) signal [7]. In fact some studies have shown contradicting and inconsistent results when CTG is used to predict fetal asphyxia [8]. Due to this lack of accuracy, standard procedures used to analyze heart rate variability (HRV) for adults are rarely used to analyze fHRV [7].

Using non-invasive ECG recordings from the mother's abdomen, the fetal ECG signal is usually dominated by the mother ECG signal and cannot be seen by direct visualization of the recordings. Not only that, but also trying to filter out the fetal ECG signal by direct bandpass filters is almost impossible due to the overlap, in the frequency domain, of the mother ECG, the fetal ECG, and the noise signals [9]. Previous studies have shown that in certain cases the extraction of fetal ECG is possible using some nonlinear techniques such as the state space projections [9] and the frequency tracking [10].

To study fHR or fHRV, all what is needed is the location of the peaks (*R* waves) of the fetal ECG and not the overall fetal ECG signal. So if we can find the locations of these *R* waves accurately, that will be enough to conduct an accurate and realistic study of fHR or fHRV.

Fourier's theorem implies that any function that periodically varies with time can be expressed as a weighted sum of sinusoidal components at frequencies f_o, $2f_o$, $3f_o$, . . . etc where f_o is called the fundamental frequency of the original function and is equal to the reciprocal of the period of that function (i.e., $f_o = 1/T$) [11]. Since both the mother and the fetal ECG signals are periodic functions, Fourier's theorem applies to both. In general, the fetus has a faster heart rate than the mother, thus the fundamental frequency of the fetal ECG signal is higher than that of the mother ECG signal ($f_{o\text{-}f} > f_{o\text{-}m}$). Since the mother ECG is the dominant signal in the recording, the mother's heart rate (*MHR*) in beats per minute (bpm) can be directly evaluated form the recorded signal. Then $f_{o\text{-}m}$, in Hz, can be easily calculated by $f_{o\text{-}m} = MHR/60$. The harmonics of the mother ECG signal are located at integer multiples of $f_{o\text{-}m}$ (i.e., $2f_{o\text{-}m}$, $3f_{o\text{-}m}$, $4f_{o\text{-}m}$ . . . etc).

Two notch filters are designed to suppress the first two harmonics ($2f_{o\text{-}m}$ and $3f_{o\text{-}m}$), then a bandpass filter is designed with the first cutoff frequency chosen slightly higher than $f_{o\text{-}m}$ and the second cutoff frequency chosen slightly lower than the third harmonic of the mother ECG signal ($4f_{o\text{-}m}$). Due to the suppression of the first two harmonics of the mother ECG signal, $f_{o\text{-}f}$ will be the major, but not the only, frequency component in the pass range of the bandpass filter. So what will pass through the filter is $f_{o\text{-}f}$ accompanied by some other frequency components that although exist, they are smaller in magnitude compared to $f_{o\text{-}f}$. These frequency components will be carried on $f_{o\text{-}f}$ without changing the basic oscillations of $f_{o\text{-}f}$.

K. Lweesy is with the Jordan University of Science and Technology, Irbid 22110, Jordan (phone: +962-777-317-391; fax: +962-2-720-1074; e-mail: klweesy@just.edu.jo).

L. Fraiwan is with the Jordan University of Science and Technology, Irbid 22110, Jordan (e-mail: fraiwan@just.edu.jo).

C. Maier is with the Heilbronn University, Heilbronn, Germany (e-mail: christoph.maier@hs-heilbronn.de).

H. Dickhaus is with the University of Heidelberg, Heidelberg, Germany (e-mail: hartmut.dickhaus@med.uni-heidelberg.de).

Taking the inverse Fourier transform of the filtered signal gives a signal in the time domain with its peak-to-peak (or zero-to-zero) values representing the *R* to *R* fluctuations (*RR* intervals). This study describes the extraction of fHR and fHRV signals by targeting the fundamental frequency of the fetal ECG signal. This method was evaluated on a simulated mixture of mother ECG, fetal ECG, and noise signals as well as on real signals obtained from 20 abdominal recordings from pregnant women at different gestational ages.

II. MATERIALS AND METHODS

Three different studies have been performed to ensure the capability of the proposed method to accurately find fHR and fHRV. In the first study, different cosine waves were modulated then filtered through the proposed method to see the impact of nearby harmonics on a certain cosine wave that resembles the fetal's fundamental frequency signal. In the second study, a simulated mother ECG signal, a simulated fetal ECG signal, and a random noise signal were added together then entered through the proposed method to investigate its capability to accurately detect both fHR and fHRV. In the third study, real ECG signals obtained from abdominal recordings of pregnant women were studied in the proposed method to evaluate fHR and fHRV. The three studies mentioned above are detailed in the following three subsections.

A. Cosine Wave Simulations

In this part, a group of cosine waves at different frequencies and amplitudes are added together to see if beat-to-beat values change as a result of adding frequency components as the block diagram in Fig. 1 shows. The used cosine signals have

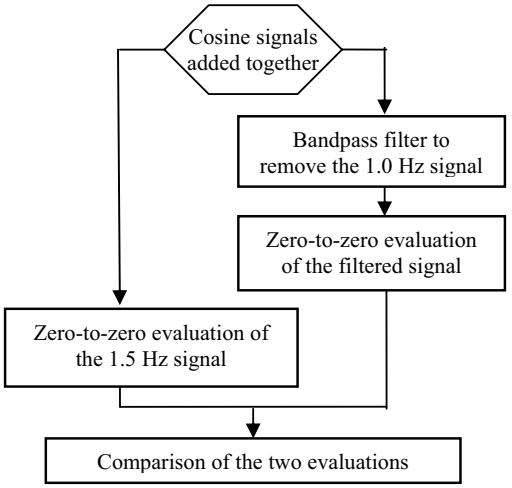

Fig. 1 Block diagram showing the different stages performed to obtain the fundamental frequency

frequencies of 1 (resembling mother's fundamental frequency), 1.3, 1.33, 1.36, 1.39, 1.42, 1.45, 1.48, 1.5 (resembling fetal's fundamental frequency), 1.52, 1.55, 1.58, 1.61, 1.64, 1.67, and 1.7 Hz, with amplitudes of 1.5, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.7, 0.4, 0.35, 0.3, 0.25, 0.2, 0.15, and 0.1, respectively. These cosine signals were summed together (summation is called $y(t)$) and their fast Fourier transform (FFT) magnitude ($|Y(f)|$) is evaluated and plotted in Fig. 2. An infinite impulse response (IIR) Chebeshev type II bandpass filter (BPF) with lower and upper cutoff frequencies of 1.15 and 1.85, respectively, was designed using Matlab (R2006a, Mathworks Inc., Natick, MA, USA).

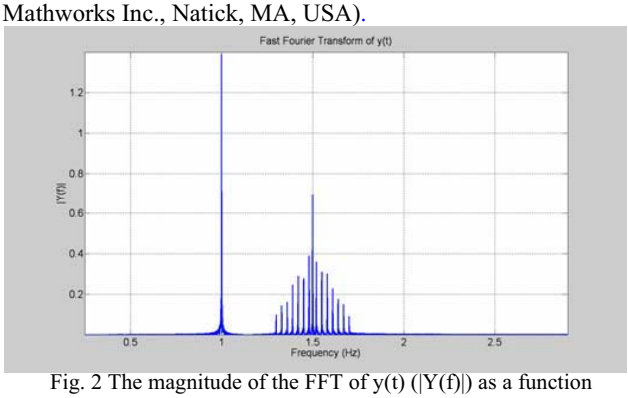

Fig. 2 The magnitude of the FFT of y(t) (|Y(f)|) as a function of frequency

B. Simulated Signals

A flowchart that shows the steps performed in this part is shown in Fig. 3. In this part, a simulated signal composed of a mother ECG signal, a fetal ECG signal, and random noise,

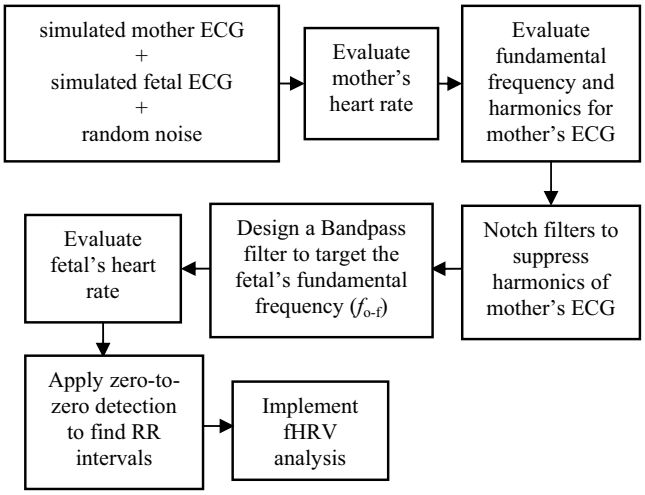

Fig. 3 Block diagram showing the different stages performed to obtain the fHRV signal

was used to check the accuracy of the technique. The simulated mother ECG signal has a heart rate of 60 bpm (thus a fundamental frequency of 1 Hz), while the simulated fetal ECG signal has a heart rate of 90 bpm (thus a fundamental frequency of 1.5 Hz). Both the mother and the fetal simulated ECG's have the same waveform but with different amplitudes and frequencies. The mother ECG simulated signal has two identical repeated parts while the fetal ECG simulated signal has three identical repeated parts. This is done to ensure that the proposed method is capable of detecting fHR and fHRV correctly. The 1 Hz mother ECG signal, the 1.5 Hz fetal ECG signal, and a random noise signal were added together forming a mixed signal (Fig. 4(a)) that mimics the mother's abdominal recording. The amplitudes of the three constituents

of this signal are 1, 0.4, and 0.05 for the mother's ECG, fetal's ECG, and noise, respectively, as can be seen in Figs. 4(b), 4(c), and 4(d), respectively.

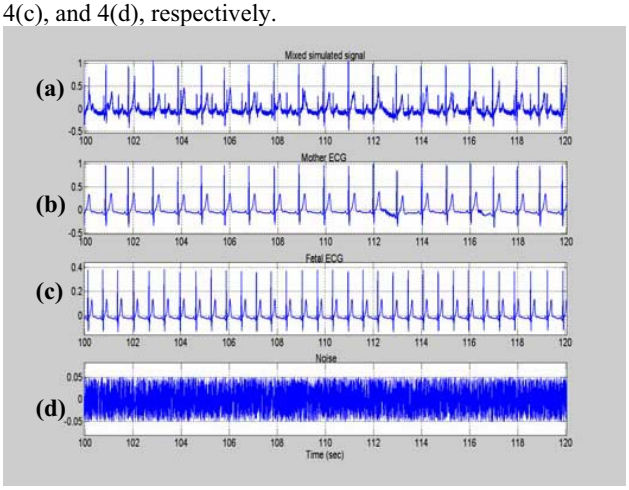

Fig. 4 The simulated signals used to verify the technique showing (a) the total signal, (b) the mother ECG signal, (c) the fetal ECG signal, and (d) the noise signal

Since the fundamental frequency of the mother's ECG signal is 1 Hz, the higher frequency harmonics occur at frequencies of 2 Hz, 3 Hz, 4 Hz, … etc. Notch filters (2 Hz, 3 Hz, and 4 Hz) to suppress these harmonics were designed using Matlab. The mixed signal is passed through these Notch filters then through a BPF similar to the one described in II.A, but with lower and upper cutoff frequencies of 1.1 Hz and 3.9 Hz, respectively. The lower cutoff frequency (1.1 Hz) was chosen slightly above the fundamental frequency of the mother's ECG signal; while the higher cutoff frequency (3.9 Hz) was chosen slightly before the third harmonic (occurs at 4 Hz). This frequency range (1.1 – 3.9 Hz) is equivalent to a heart rate range of (66 – 234 bpm), which includes the fetal's heart rate. The designed BPF was an infinite impulse response (IIR) Chebyshev filter (type II) of order 238 and a sampling frequency of 500 Hz.

C. Real Signals Study

The block diagram in Fig. 3 was used here but with ''Abdominal mother ECG signal'' replacing ''simulated mother ECG + simulated fetal ECG + random noise''. The abdominal mother ECG signal was obtained using a sampling frequency of 500 Hz.

Notch filters to suppress the first two harmonics at 3.28 Hz and 4.92 Hz were designed and implemented. A BPF with its lower cutoff frequency chosen slightly higher than 1.64 Hz (the mother's ECG fundamental frequency) and its higher cutoff frequency chosen slightly lower than 6.56 Hz (the third harmonic of the mother's ECG signal) was designed.

III. RESULTS

A. Cosine Wave Simulations

Passing the signal $|Y(f)|$ through the designed BPF resulted in rejecting the 1 Hz signal. As a result, the output filtered signal ($y_o(t)$) has all the frequency components in $y(t)$ except the 1 Hz frequency. The 1.5 Hz signal and the filtered signal ($y_o(t)$) are plotted as a function of time (Fig. 5(a)) for comparison. Fig. 5(a) and the zoom in (Fig. 5(b)) indicate that although the signal $y_o(t)$ (blue) consists of many frequency components, the peak-to-peak (or the zero-to-zero) values are exactly the same as those for the 1.5 Hz signal.

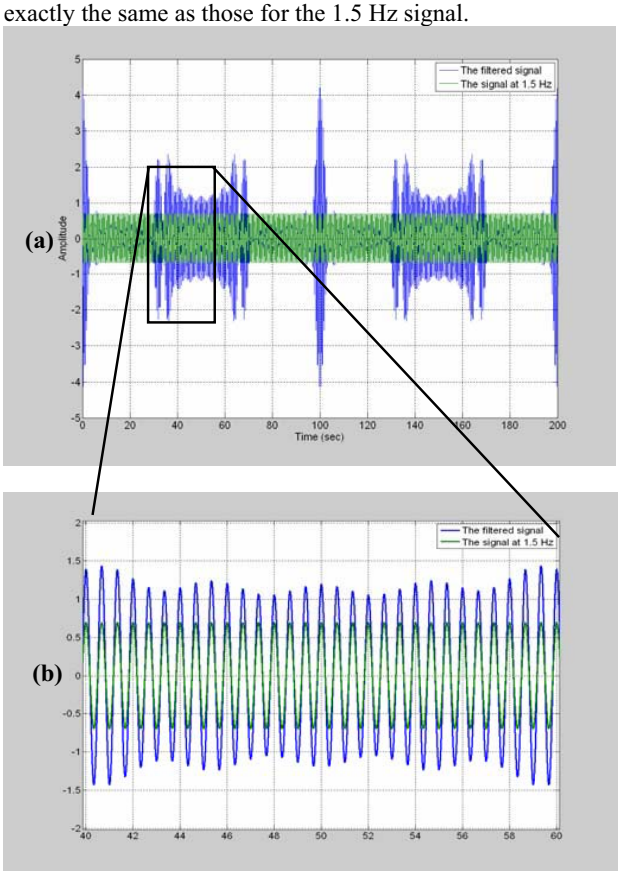

Fig. 5 (a) Comparison of the filtered signal and the 1.5 Hz signal and (b) a zoom in

B. Simulated Signals

The output of the BPF is then compared with the simulated fetal ECG signal, as shown in Fig. 6; which clearly indicates that the filtration process was successful in obtaining the fundamental oscillation of the fetal ECG signal. To make sure that the beat-to-beat oscillations, or the *RR* intervals, are preserved in the filtration process, the *RR* intervals from the original fetal ECG signal, and the peak-to-peak (or zero-to-zero) values of the extracted fundamental signal, were evaluated and compared. Fig. 7 shows a plot of those two evaluations and shows also the *RR* plot for the mother's simulated ECG signal. A clear similarity of the two fetal evaluations indicates that the beat-to-beat changes are preserved to a large extent.

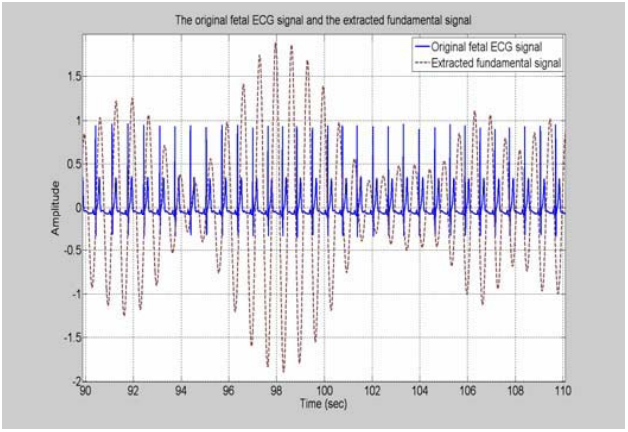

Fig. 6 A plot of the original simulated fetal ECG signal and the extracted fundamental frequency of the fetal's ECG signal

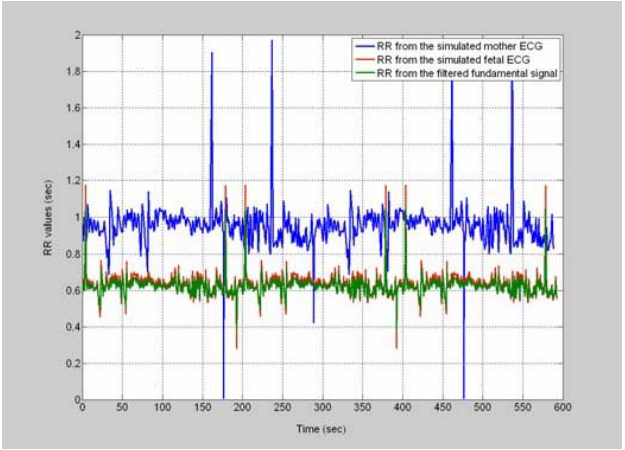

Fig. 7 Plot of the *RR* values as a function of time for the simulated mother ECG, the simulated fetal ECG, and the filtered fundamental signal

C. Real Signals Study

A plot of a 5 second sample of one of the recordings is shown in Fig. 8 with the *R*'s indicating the locations of the *R* wave for the mother's signal. For this example, the mother has a heart rate of about 98.4 bpm, an *RR* value in the range of 0.61 sec, and a fundamental frequency of about 1.64 Hz. After passing the mother's abdominal ECG signal through the Notch filters then through the BPF, the resultant output was saved for processing. It was a cosine wave oscillating at the fetal's fundamental frequency with some smaller harmonics carried on it (Fig. 9(a)). A zoom in for this signal is shown in Fig. 9(b) indicating the *R* locations for the fetal ECG. For this case, the fetal heart rate was about 186 bpm and the fetal's fundamental frequency was about 3.11 Hz.

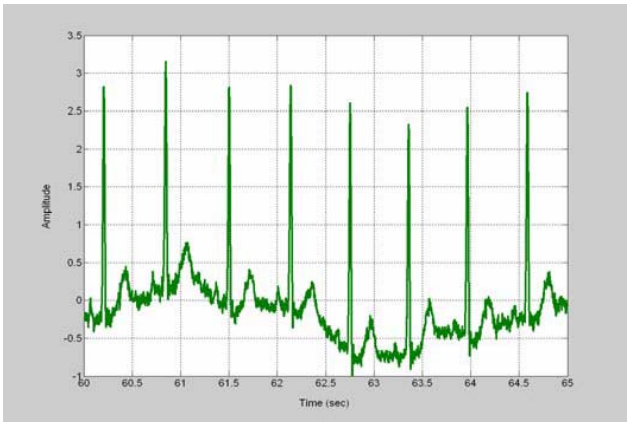

Fig. 8 A plot of a 5 second recording of a real abdominal pregnant mother ECG signal

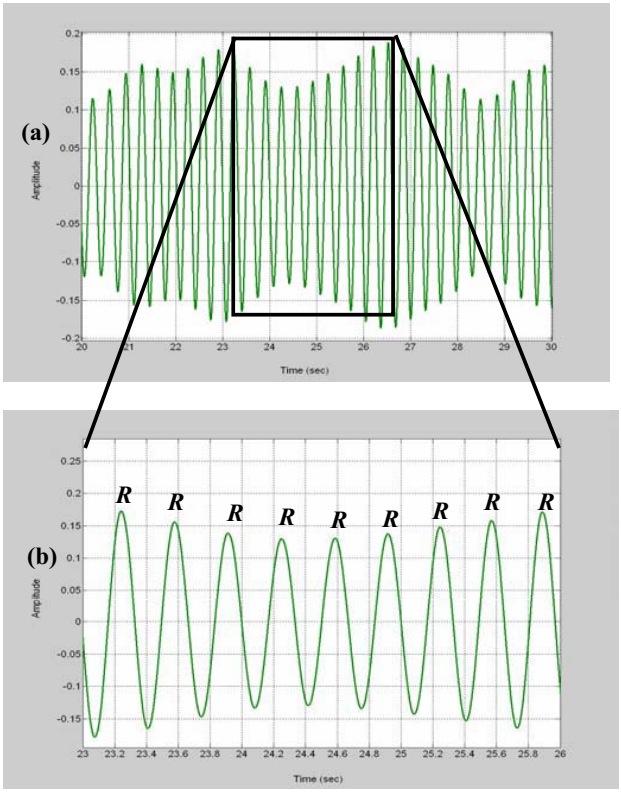

Fig. 9 (a) The filtered fundamental frequency of the fetal's real ECG signal and (b) a zoom in

We have shown in this study that accurate extraction of the fHR value and the fHRV signal is possible. The extraction process starts by determining the fundamental frequency of the mother's ECG signal, which is then used to design the Notch and bandpass filters.

The method described herein was capable of accurately extracting fHR and fHRV for simulated signals. The method was then used to extract the fHR value and the fHRV signal for real abdominal ECG recordings obtained form a pregnant woman's abdomen.

IV. DISCUSSION

Both fHR and fHRV are important for identifying fetal's wellbeing and giving early alarms about those who might be at higher risk of some important diseases, such as SIDS and supraventricular extrasystoles. Existing techniques to evaluate both fHR and fHRV depend on non-accurate fetal ECG measurements obtained using CTG machines.

Since both fHR and fHRV depend on *RR* intervals, the availability of the fundamental frequency of the fetal's ECG signal is enough to evaluate both fHR and fHRV, without the need to have the fetal's ECG signal itself.

In the method described in this paper, the extraction process starts by determining the fundamental frequency and the higher frequency harmonics of the mother's ECG signal, which are directly calculated from the abdominal recorded signal. Then Notch filters to suppress the harmonics, and a BPF to target the fundamental frequency of the fetal's ECG signal, are designed and implemented.

Both simulated and true signals were used to check the capability of the method in detecting the fHR value and the fHRV signal. The obtained results indicate that accurate fHR and fHRV can be detected using ECG signals recorded from the mother's abdomen.

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