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SPECTRAL ANALYSIS OF THE FETAL ELECTROCARDIOGRAM*

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Abstract—The spectral curves of the averaged fetal and maternal electrocardiograms as recorded from the abdomen were studied. The power spectrums were obtained using a technique which includes the subtraction of an averaged maternal ECG waveform using cross-correlation function and fast Fourier transform algorithm. The spectral curves of the averaged maternal and fetal ECG waveforms obtained from 21 pregnant women who had gestation periods of 32 41 weeks were studied. It was found that the poor signal to noise ratio, the high rate of coincidence between maternal and fetal ECGs and the similar frequency spectra of the signal and the noise components make an analysis of the abdominal ECG using conventional filtering technique rarely possible and an alternative method should be used.

Fetal monitoring Abdominal ECG Signal averaging Cross-correlation
Fourier transform Power spectrum

1. INTRODUCTION

The electrocardiogram is the most suitable method for accurate beat to beat determination of the fetal heart rate [1]. Recently [2–4] new techniques were introduced for the suppression of the maternal ECG from the abdominal signal and introducing only the fetal waveforms. A question is raised if an analysis of the fetal ECG using conventional filtering technique is possible. In the present study the spectral curves of the maternal and fetal averaged ECG waveforms obtained from 21 pregnant women who had gestation periods of 32–41 weeks were studied in order to determine if the conventional filtering process can separate between the maternal and the fetal ECG waveforms.

MATERIALS AND METHODS

The recording procedure

Recordings were made utilizing two silver–silver chloride electrodes at the back and on the abdomen with the patient in the supine position. The abdominal ECG waveforms were stored on a tape (TEAC R-60 FM recorder) for later playback and analysis. On playback, the recorded analog data were passed through a low pass 8 pole Butterworth anti-aliasing filter with high frequency cutoff at 100 Hz and digitized using a 12 bit analog to digital converter at a sampling rate of 1000 Hz. The processing of the digitized data took place off-line using an Olivetti M380 XP1 personal computer with 80387 co-processor.

The averaging process

On playback an averaged maternal signal is obtained using cross-correlation function [5, 6] and digital filters [7]. The cross-correlation function was calculated by the cross-spectrum and the fast Fourier transform algorithm. The maximum value of the cross-correlation function and the time location of that value were searched for (a) the similarity

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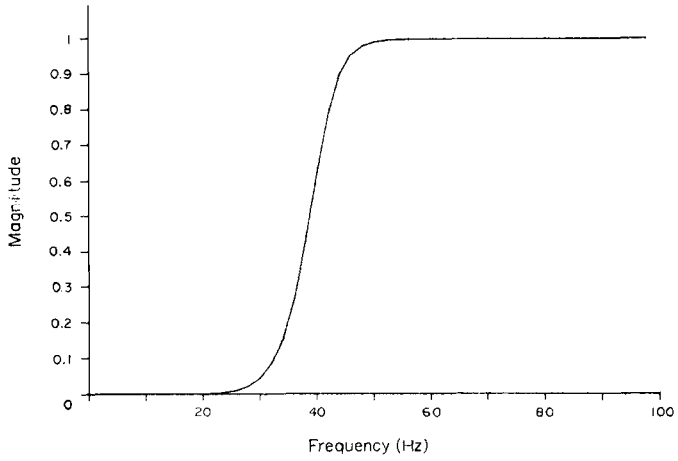

Fig. 1. The frequency response of the high-pass non-recursive digital filter with low-frequency cut-off at 40 Hz.

between the waveforms (for elimination of artifacts) and (b) measuring the relative time delay (for the waveform's alignment in the averaging process) between the ECG waveforms. With this procedure a template signal corresponding to one complete maternal ECG signal is obtained. The fetal ECG and the electromyogram are suppressed in the maternal template waveform since they are not correlated with the maternal ECG. The averaged maternal ECG was then subtracted from the abdominal signals and results in complete elimination of the maternal signal. It is thus possible to detect all the fetal QRS complexes in spite of their coincidence with the maternal ECG. An averaged fetal ECG is then extracted using the same averaging process.

The power spectrum

The spectral content of the averaged maternal and fetal ECG waveforms were analyzed using power spectrum algorithm. The power spectrum, represented as the sum of the squares of the real and imaginary parts of the Fourier transform of the averaged signals, was calculated and analyzed.

$$P(F_i) = A^2(F_i) + B^2(F_i)$$

where $A(F_i)$ and $B(F_i)$ are the real and imaginary Fourier coefficients at frequency F_i of the transformed signal, respectively. The spectral curves of the averaged maternal and fetal QRS complexes determined the frequency response of the filter to be used in order to separate the fetal ECG from the maternal one using the conventional filtering process.

The filtering process

The averaged waveforms were passed through a non-recursive two-pole Butterworth digital high-pass filter with low frequency cut-off at 40 Hz (Fig. 1). The filtering process took place in the frequency (Fourier domain) using the fast Fourier transform algorithm.

Let the response of a non-recursive digital filter, $h(t)$, to an excitation $x(t)$ (the ECG waveform) be $z(t)$. This response of the filter can be computed by using the following procedure.

(1) Compute $H(s)$ and $X(s)$ which are the Fourier transform of $h(t)$ and $x(t)$, respectively.
(2) Compute the product $Z(s) = H(s)X(s)$.
(3) Compute the inverse Fourier transform of $Z(s)$ which is equal to $z(t)$.

RESULTS

Figure 2 shows a typical example of the spectral curves obtained from the averaged maternal and fetal QRS complexes. As can be seen the energy content of the maternal

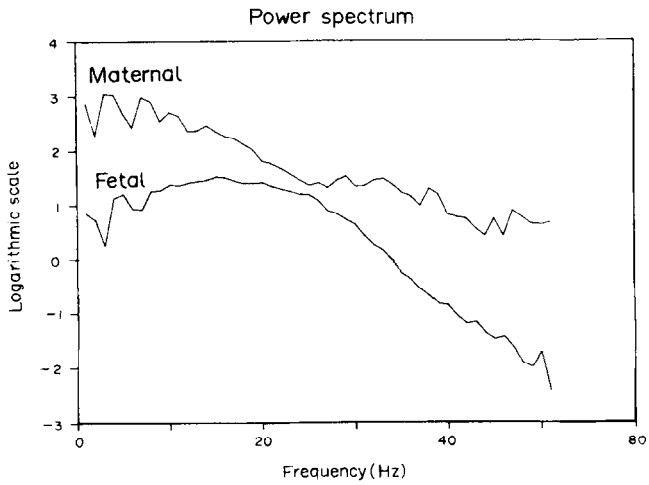

Fig. 2. A typical example of the spectral curves obtained from the averaged maternal (upper trace) and fetal (lower trace) QRS complexes. As can be seen the energy content of the maternal QRS complex is higher than the fetal one all over the frequency range.

QRS complex is higher than the fetal one all over the frequency range. Figure 3 shows abdominal ECG waveforms (upper trace) and the same waveforms filtered with low pass filter with high frequency cutoff at 20 Hz (lower trace). As can be seen applying low pass filtering suppressed the fetal ECG and only the maternal complex is present. However, because of the high energy content of the maternal QRS complex, compared to the fetal, presenting the fetal ECGs after suppressing the maternal QRS complexes using conventional filtering process could be performed only in one out of 21 abdominal recordings. This case (presented in the next figures) showed high amplitude fetal ECG (see Fig. 4) and using high pass filtering, which suppressed the maternal ECG, the fetal ECG could be obtained. Figure 5 shows a single (lower trace) and an averaged (upper trace) maternal ECG waveform. The noise and the fetal ECGs (f) which were present in the single waveform are suppressed in the averaged MECG. Figure 6 shows abdominal ECG waveforms (upper trace) and the fetal ECG waveforms (lower trace) after subtracting the averaged maternal signal shown in Fig. 5 (lower trace). As can be seen it is now possible to detect the fetal QRS complexes in spite of their coincidence with the maternal signal. Figure 7 is the average of 100 fetal ECGs. Figure 8 shows the spectral curves obtained from the averaged maternal and fetal QRS complexes. As can be seen the energy content of the fetal QRS complex is higher than the maternal over the high frequency range (30 Hz and up). Figure 9 shows abdominal ECG waveforms (upper trace), and the same waveforms filtered with

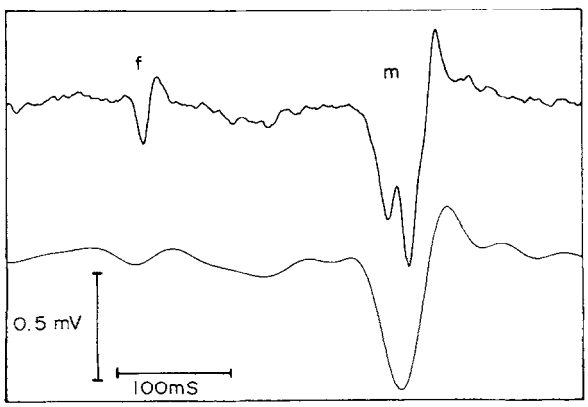

Fig. 3. Abdominal ECG waveforms (upper trace) and the same waveforms filtered with low pass filter with high frequency cutoff at 20 Hz (lower trace). As can be seen applying low pass filtering suppressed the fetal ECG and only the maternal complex is present.

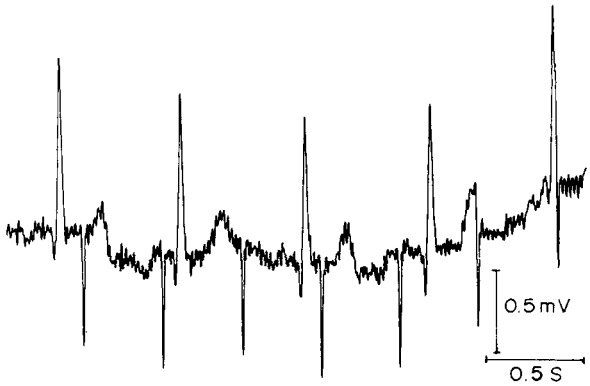

Fig. 4. An example of abdominal recording with high amplitude fetal ECG waveforms.

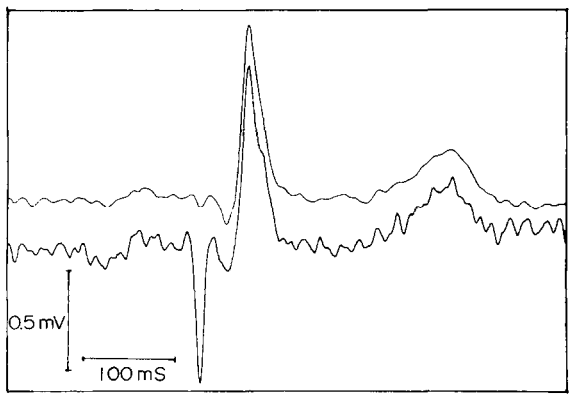

Fig. 5. A single maternal ECG waveform (lower trace) and an averaged maternal ECG (upper trace). The noise and the fetal ECG which were present in the single waveform are suppressed in the averaged MECG.

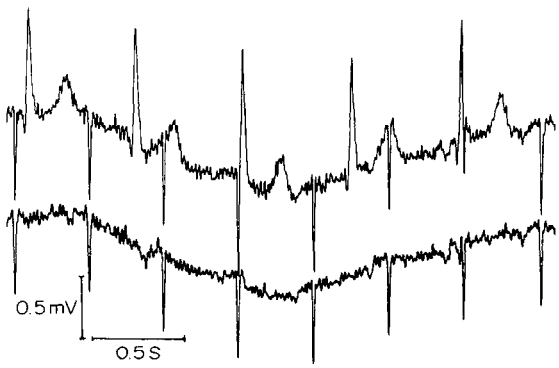

Fig. 6. Recorded abdominal ECG waveforms before (upper trace) and after (lower trace) subtracting the averaged maternal ECG shown in Fig. 5 upper trace. The fetal QRS complexes can be recognized in spite of their coincidence with the maternal signal.

high pass filter with low frequency cutoff at 40 Hz are presented in Fig. 1. As can be seen applying high pass filtering suppressed the maternal ECG, and only the fetal QRS complexes are present. The beat-to-beat maternal and fetal heart rate information are presented in Fig. 10.

SUMMARY

Fetal ECG monitoring enables accurate measurement of fetal cardiac performance including transient or permanent abnormalities of rhythm and parameters for the assessment

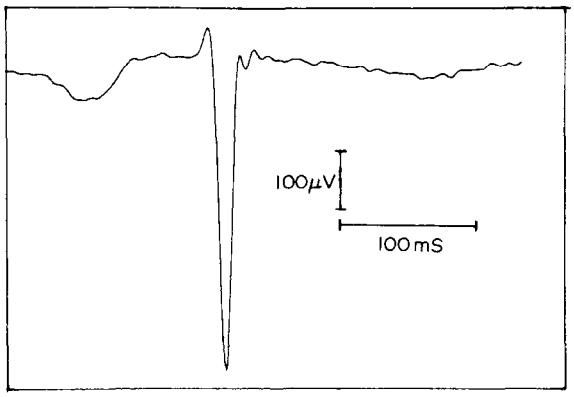

Fig. 7. Averaged fetal ECG waveform.

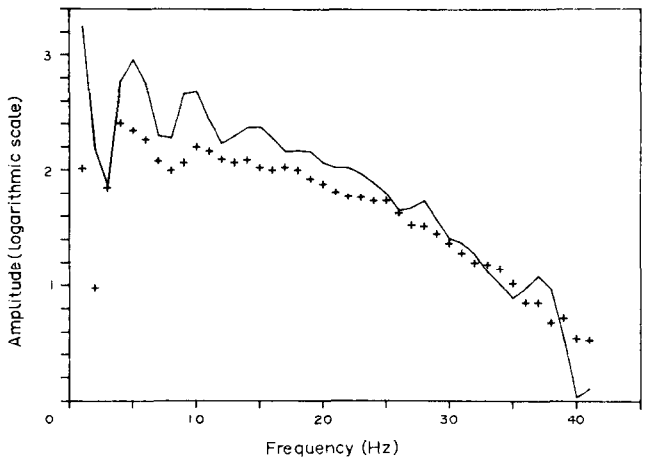

Fig. 8. The spectral curves obtained from the averaged maternal (—)and fetal (+) QRS complexes shown in Figs 5 and 7. As can be seen the energy content of the fetal QRS complex is higher than the maternal one over the high frequency range (about 30 Hz plus).

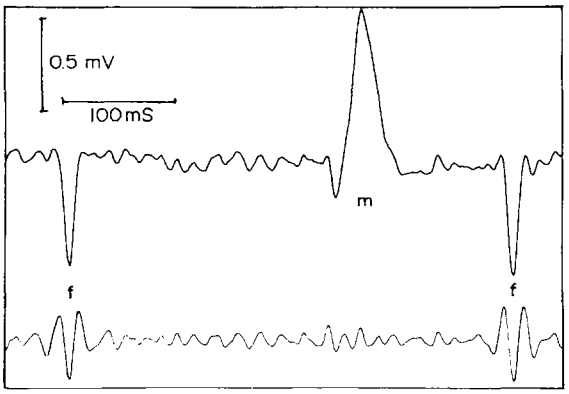

Fig. 9. Abdominal ECG waveforms (upper trace) and the same waveforms filtered with high pass filter (lower trace) with low frequency cutoff at 40 Hz presented in Fig. 1. As can be seen applying high pass filtering suppressed the maternal ECG and only the fetal QRS complexes are present.

of fetal hypoxemia or acidosis [8, 9]. Furthermore, heart rate variability enables definition of the autonomic central nervous system [10]. These measurements may provide important predictors of fetal well-being.

In the present project the abdominal ECG waveform was studied, using power spectrum analysis and Fourier transform algorithm, to determine if the conventional filtering process

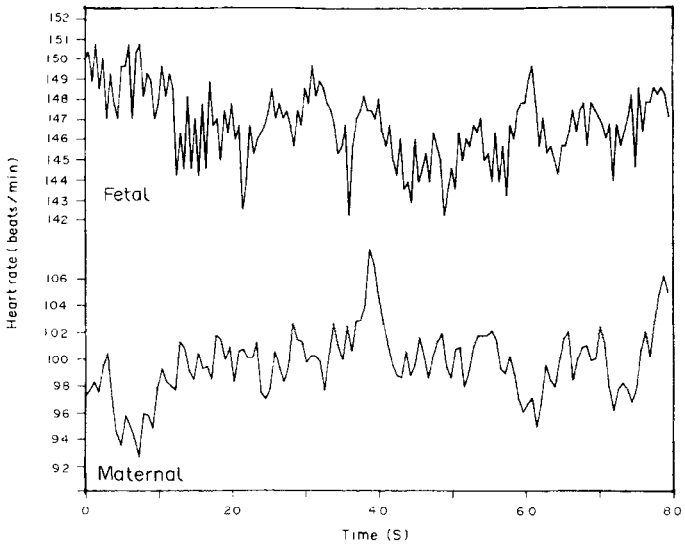

Fig. 10. The beat-to-beat maternal and fetal heart rates information.

can be used to separate the maternal and the fetal ECG waveforms. The averaged maternal ECG waveform was obtained and subtracted from the abdominal ECG using the cross-correlation function for accurate alignment between the averaged ECG and each of the following waveforms. After eliminating the maternal ECG from the abdominal recording, the temporal location of the fetal QRS complexes was determined and an averaged fetal ECG was obtained. The power spectra of the averaged maternal and fetal QRS complexes were calculated using fast Fourier transform algorithm. In 20 out of 21 pregnant women the energy content of the maternal QRS complex was found to be higher than that of the fetal, and high-pass filtering could not be used to separate the two waveforms. Only in one abdominal recording with very high fetal ECG complexes did the filtering process enable the detection of the fetal waveforms after suppressing the maternal ECG.

Based on the results of this study, it was found that the poor signal-to-noise ratio, the high rate of coincidence between maternal and fetal ECGs and the similar frequency spectra of the signal and the noise components made an analysis of the ECG using conventional filtering technique rarely possible and a difference method should be used. An alternative technique using a subtraction algorithm of an averaged maternal ECG from the abdominal signal was introduced. For exact subtraction of the maternal ECG, it was necessary for the fiducial point in the alignment procedure between the averaged maternal ECG and each of the following waveforms to be highly accurate. A jitter of 1 ms could produce artifacts in such a way that false fetal signals would be detected. This condition of highly accurate waveform alignment cannot be satisfied in all cases by simple threshold detection and the superposition of the fetal and maternal ECGs with the noise level sometimes leads to a jitter during the maternal R wave detection. In order to prevent this false fetal ECG detection the maternal ECG waveforms were analyzed using a cross-correlation procedure for averaging the original maternal ECGs and for the subtraction procedure. This method enabled localization of maternal and fetal ECGs.

In summary, there is an increasing understanding of the clinical significance of fetal heart rate variability [11], and with the development of microprocessor technology a clinical fetal monitoring system can be developed.

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