ON THE WAVELET ANALYSIS OF THE DOPPLER SIGNALS OF FETAL ACTIVITY

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ABSTRACT

The db10 wavelet was applied to the decomposition of the ultrasonic Doppler signals recorded on the abdomen of a pregnant woman. The correlation analysis of the wavelet reconstruction products enabled the detection of signals due to movements of fetal cardiac structures, fetal pseudo-breathing and hiccups, maternal breathing and cardiac movements, the estimation of the corresponding rhythms, and the evaluation of the frequency ranges of the corresponding signals. Bandwidths of Doppler signals resulting from the movements of fetal cardiac structures overlap only partly with those resulting from the pseudo-breathing and the fetal hiccup. Doppler signals of maternal origin feature lower frequency contents or lower rhythms than the signals of the fetal origin and are expected not to adversely affect the estimation of the fetal rhythms. These findings may be exploited in the development of the Doppler hardware used for the collection of fetal activity signals and in the identification of signals resulting from individual fetal activities.

KEY WORDS
Wavelet transform, Doppler signals, fetal activity, correlation, pseudo-breathing

1. Introduction

Fetal activity is an important indicator of fetal well-being, in particular presence of fetal pseudo-breathing movements [1, 2, 3]. The introduction of fetal activity monitoring was expected to reduce the incidence of cerebral palsy, commonly ascribed to intrauterine asphyxia. The assessment of this activity includes various techniques, from fetal movement counting performed by mothers to multiple technical means for the detection of these movements, e.g. inductive transducers [4] or electrical impedance method [5]. The technique dominating now is the echography [6]. The Doppler ultrasound also plays an important role in the detection of fetal movements [7-17]. The currently used methods for the assessment of fetal well-being include electronic fetal monitoring (cardiotocography CTG) and the biophysical profile [1]. CTG, created to trace fetal heart rate and uterine activity, can be supplemented with fetal gross body movement detection and indication. However, identification of the kind of fetal movement is not possible. Close to the CTG is the so-called fetal actocardiogram [7,14,18], however, the data provided is limited to the detection of periods of fetal activity and quiescence, and any information on the type of fetal movements is not available.

The biophysical profile (BPP) has been introduced to predict more accurately the presence or absence of asphyxia and has become a standard tool for providing antepartum fetal surveillance. Three out of five parameters integrated in the BPP describe fetal motor activity: presence of fetal breathing movements, presence of gross body movements, and the tone [1]. The BPP is frequently supplemented with the FHR recording. The BPP method involves extensive use of ultrasonography and the examination may last up to approximately half an hour.

Summarizing, the methods mentioned are expected to provide information on the fetal heart rate and presence of fetal movements. Particular importance is attached to the presence of pseudo-breathing episodes. This information may be extracted from ultrasonic Doppler signals resulting from movements of fetal body structures using suitable signal processing techniques. The quadrature components of the Doppler signal obtained using the continuous wave (CW) or pulsed wave (PW) Doppler device are analysed [10-16]. The autocorrelation technique is usually applied to the Doppler signal to obtain the FHR [19]. Alternatively, parameters derived from the analytical Doppler signal may be submitted to spectral analysis to obtain information on cardiac and pseudo-breathing rhythms [16]. The fetal pseudo-breathing movements may also be detected using the procedure presented in [10], or on the basis of the Fourier analysis or autoregressive-modelling based spectral analysis of filtered Doppler signals [12,16]. An interesting idea relying on application of multiple ultrasonic transducers and source separation methods to study of fetal activity has recently been presented [17].

Although various processing techniques have been studied and several hardware solutions have been proposed,
the methods of collection and analysis of the Doppler signals of fetal activity still present subject of research. As the fetal activity and other phenomena under consideration may result in periodic or quasi-periodic events, like the movements of the fetal thorax and cardiac structures (Fig.1), it seems of interest to apply methods resulting in better localization of these events in the time-frequency than classical filtering or spectral analysis techniques can provide. One of such methods is the wavelet transform, applied to the detection of the pseudo-breathing movements in fetal lamb [20] and other Doppler signals [21]. Below presented is an application of the wavelet transform to the detection of the signals resulting from the movements of fetal cardiac structures and fetal breathing movements, as well as of other phenomena in the Doppler signal of fetal activity, collected on the surface of the maternal abdomen. The analysis of periodicity of the wavelet reconstruction products is expected to provide information on rhythms potentially present in the environment under consideration, e.g. the FHR or the fetal pseudo-breathing rate. This analysis is also expected to enable the assessment of the frequency ranges of the Doppler signals resulting from various movements. The study is based on 20 recordings of Doppler signals of fetal activity.

Fig.1. M-mode ultrasonographic image of the fetus. Arrows indicate pseudo-breathing movements (upper) and movements of cardiac structures (lower).

2. Material and Methods

2.1. Hardware

The signals were collected using a laboratory built 2MHz CW Doppler device. The acoustic power density at the transducer surface is below 8mW/cm². The system uses battery supply to ensure patient’s safety. The Doppler device provides two quadrature output audio signals with bandwidth of 20-200Hz, resulting from the use of 4th order Butterworth lowpass and highpass filters. The output signals are fed to the line inputs of the soundcard of a laptop PC computer and digitized at a rate of 400Hz with a resolution of 16 bits.

Fig.2. Quadrature Doppler signals of fetal activity, resulting from two bidirectional movements (a) and the corresponding directional signals (b). Plot of the db10 wavelet (c). Scaling: abscissa – sample number, ordinate – arbitrary units.

2.2. Data collection

The fetal data were acquired in the 2nd Department of Obstetrics and Gynecology, Medical University of Warsaw. The study protocol was accepted by the Human Investigation Committee of the University. Prior to the recording the fetal heart and diaphragm were localized using an ul-
trasonicograph, enabling right positioning of the ultrasonic probe on the maternal abdomen. 20 recordings lasting 15-20 minutes, obtained from third trimester pregnancies, were submitted to this study.

2.3. Data processing
The quadrature Doppler signals (Fig.2a) were submitted to the Hilbert transform, then exploiting the phase relations inherent to such signals and their Hilbert transforms two directional Doppler signals were obtained [22]. Each of these signals carries information on movements in one direction only (Fig.2b), which facilitates the interpretation of autocorrelation peaks, as broadened or closely spaced peaks, potentially present in the case of the quadrature signal, are avoided. The wavelet decomposition was applied to the directional signals. As the signal under consideration is composed of quasi-sinusoidal events with smooth onset and decay, wavelet db10 with similar properties was used in this study (Fig. 2c) [23]. These wavelets are equivalent to a bank of the octave filters with non-overlapping bands, thus ensuring signal decomposition without redundancy [24]. The transform was carried out for scales 2, 4, 8 and 16, resulting in details D1-D4 and approximation A4. After the reconstruction these products fell respectively into the frequency bands 100Hz-200Hz, 50Hz-100Hz, 25Hz-50Hz, 12.5Hz-25Hz, 0Hz-12.5Hz. The DWT reconstruction products were inspected for presence of periodic events. The moduli of the reconstructed DWT details, as well as the modulus of the directional Doppler signal, were submitted to the correlation analysis for detection of periodic events. The autocorrelation coefficients (ACC) were computed for data windows with 50% overlap and lengths from 2.5s to 8s. The autocorrelation lags covered the same range. The correlation analysis was applied to the reconstruction products of the DWT, not to the DWT coefficients, to facilitate comparisons of results – a periodic event resulted in an ACC peak for the same delay for reconstruction products at all scales. A peak in the ACC of any wavelet reconstruction product was indicative of the presence of the periodic signal in the corresponding frequency range. Taking into account available data on the frequency of the fetal [3,9] and maternal rhythms, the frequency ranges of the signals resulting from individual activities were assessed. The processing was carried out within the MATLAB environment.

3. Results
The example of the results of the DWT reconstruction and correlation analysis of the directional Doppler signal indicates presence of two periodic phenomena (Fig.3). One can be seen in the reconstruction details D1 and D2, the other in the details D3 and D4, as well as in the original signal. The delay of the first maximum of ACC of these coefficients allows the identification of these two periodicities. First phenomenon, with a period of approx. 170 samples, i.e. 425ms, corresponds to FHR of 140/min. The second, with period of approx. 370 samples (925ms), corresponds to a pseudo-respiration rate 65/min (Fig.3). Trace of the second periodicity can also be seen in the plot of the ACC of the detail D2 in the slightly increased second peak with respect to the first one. The example of the autocorrelation map for an entire recording shows presence of peaks for delays corresponding to the periodicity of the movements of the fetal cardiac structures (Fig.4). Another autocorrelation map of the reconstructed
detail D3 shows presence of irregular periodicity with a period approximately 400-600 samples, i.e. 0.66 – 1s, corresponding to the fetal pseudo-breathing activity (Fig.5). Strong maxima due to the fetal cardiac periodicity appear from the correlation window number 75 onwards (Fig.5).

Fig.4. Autocorrelation coefficient map of the D1 reconstruction product of a signal resulting from movements of fetal cardiac structures. Scaling: abscissa – lag at a sampling rate of 400Hz, ordinate – correlation window number. The window length and lag are specified in number of samples in the figure.

The DWT decomposition and reconstruction using the db10 wavelet and subsequent correlation analysis of these products of all 20 recordings allow to say that the information on the cardiac periodicity is present mainly in the reconstruction detail D1 – 85% of cases analysed (Fig.6). Only 3 recordings contained no cardiac signal in the detail D1. In one of such cases this signal was present in the details D2 and D3, in the remaining two – in the details D2-D4. The cardiac information was thus always present in at least one of the details D1 and D2, and in at least two of the details D1-D3. The detail D2 carried the cardiac information in 75% of the recordings, details D3 and D4 – in 65% and 55%, respectively. The approximation A4 product, which corresponds to velocities below 5mm/s, showed a weak cardiac signal in 15% of cases (2 recordings). The directional Doppler signal showed presence of the cardiac information in 50% of recordings analysed. The necessary condition was the lack of other simultaneous movements, like fetal or maternal body movements, which would have resulted in a stronger signal, masking the weaker signal due to the movements of fetal cardiac structures. Thus, the velocities of movements of fetal cardiac structures (in the direction of ultrasound propagation) observed in this study were always present in the range 20-75mm/s, fell mainly in the range 10-75mm/s, however, lower velocities in the range 5-10mm/s were also observed in approximately 55% of cases.

Signals resulting from the fetal pseudorespiratory activity were detected in 9 recordings. The corresponding information was visible in the directional Doppler signal and was always present in the detail D4 at scale 16, in 78% of cases in the detail D3, scale 8 (Fig. 6). In 67% of cases it
was also present in the approximation A4 signal. Therefore, the velocities due to the breathing movements did not exceed 20mm/s and were always present in the range approximately 5-10mm/s. Signals due to movements with velocities below 7.5mm/s are attenuated by the Doppler device hardware.

![Wavelet reconstruction products](image)

**Fig.7.** Wavelet reconstruction products of the recording containing hiccup signal (a); scaling as in Fig.3. Autocorrelation coefficient map of the reconstructed detail D4. ACC peaks of the hiccup signal are seen for windows 7-20, lags 500-900; scaling as in Fig.4.

Another phenomenon observed in the recording and the products of the wavelet reconstruction is the fetal hiccup. These movements can be identified by watching the behaviour of the surface of the maternal abdomen. The events with a period in the vicinity of 500-900 samples (0.4Hz – 0.8Hz) can be seen in the signal, details D4, D3 and approximation, sample range approx. 5000-13000 (Fig.7a). The highest amplitudes of the hiccup–related signal are present mainly in the low frequency range, i.e. in the detail D4.

The analysis of another recording enabled the detection of an event with varying periodicity in the reconstructed detail D4, the A4 approximation and the directional Doppler signal. The maxima of the ACC of these products occur for lag approximately 1400 (17/min.). Its periodicity suggests the maternal breathing as the origin.

A periodic phenomenon was observed in yet another recording. The ACC maps of both the signal and A4 approximation showed maxima in the vicinity of lag 270, corresponding to a periodicity of 88/min. This was found to be the maternal heart rate, confirmed by the maternal cardiac rhythm examination. Apparently the fetus was displaced by the movements of the maternal cardiac structures.

### 3. Discussion and conclusions

The products of the wavelet decomposition and reconstruction give insight into signal phenomena resulting from different fetal activities, fetal movements or maternal movements, allowing the analysis of the contents of Doppler signals at different scale levels, in non-overlapping frequency bands. This enables the collection of information on the frequency ranges of the phenomena observed, thus on velocities of movements of fetal cardiac structures, of pseudo-breathing activity and other movements, like fetal hiccup and maternal breathing. It is supported by the analysis of the autocorrelation coefficients of the wavelet reconstruction products. The periodic phenomena detected are due to movements of fetal cardiac structures, pseudo-breathing movements, fetal hiccups, maternal cardiac action and maternal breathing. Considering the ACC plots, the wavelet transform seems an adequate tool for the decomposition of the Doppler signals of fetal activity for further correlation analysis and estimation of fetal rhythms.

An important observation is that the bandwidths of Doppler signals due to the movements of fetal cardiac structures and of those due to the pseudo-breathing do not overlap in a way rendering impossible separation of these signals using the wavelet decomposition. The cardiac information is always present in details at lower scales than the signal due to the pseudorespiratory movements. This justifies the use of the simple continuous wave hardware for simultaneous collection of both kinds of data. The major part of the energy of the Doppler signal due to the fetal hiccup is also situated in the frequency range below that of the signal due to the movements of cardiac structures of the fetus.

The maternal periodic activities result in Doppler signals in lower frequency range, like fetal displacements due to the maternal cardiac action, giving rise to signals present in the approximation product at scale 16, or the periodicity of these signals is significantly different from fetal
periodicities, as it is in the case of the signal resulting from fetal displacements provoked by the maternal breathing. Therefore, these signals are expected not to hinder the estimation of the fetal rhythms.

Summarizing, in the acquisition conditions like in this study (ultrasound emission frequency 2MHz, sampling frequency 400Hz) the correlation analysis of discrete wavelet transform reconstruction products D1 and D2, thus in the frequency range 50Hz-200Hz, is expected to provide data on the FHR. Similarly, the correlation analysis of the D4 product (range 12.5Hz-25Hz) is expected to provide information on the rhythm of the fetal pseudobreathing, provided that this phenomenon took place during the recording of the Doppler signals.

The findings of this study may be useful for the development of the Doppler hardware used for the collection of fetal activity signals, for the identification of signals episodes resulting from different fetal activities, thus facilitating development of algorithms for processing these signals.

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