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● *Original Contribution*

THE ACTIFETUS SYSTEM: A MULTIDOPPLER SENSOR SYSTEM FOR MONITORING FETAL MOVEMENTS

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Abstract—Fetal heart rate (FHR) monitoring is a crucial part of monitoring at-risk pregnancies and labor. Its aim is to detect any abnormalities that might indicate acute fetal distress and a need for rapid treatment to avoid death or serious sequelae, including cerebral handicap. The use of fetal biophysical profiles in high-risk pregnancies (gravidic hypertension, *in utero* infection, *etc.*) helps to distinguish healthy fetuses from those with chronic conditions. Fetal biophysical profile scores have been developed that integrate five biophysical parameters, one of which is derived from the FHR. The major parameters detected are the rate of fetal movements, fetal tone, fetal breathing movement and amniotic fluid volume. All of those parameters except FHR are obtained by prolonged echographic observation and cannot be used routinely. We developed in this study a new multigate multitransducer pulsed Doppler system for survey of fetal behavior. Fast Fourier transform and autocorrelation function have been used for processing and analyzing ultrasonic Doppler signals generated by fetal movements. Several parameters are analyzed in each of the 12 × 5 = 60 Doppler gates: amplitude of signals reflected by moving fetal structures, velocity, direction and amplitude of displacement of fetal structure (heart, chest, limbs). From these parameters it is possible to calculate FHR and characterize fetal activity. Preliminary *in vivo* results obtained in 15 pregnant women (30 to 36 wk) are very encouraging but they have yet to be confirmed in future studies. These results also demonstrate the advantages of transducers designed for improved fetal movement detection. The algorithms needs to be precise enough to allow the Actifetus system to function in real time. We now have at our disposal some algorithms that succeed in quantifying FHR and fetal movements with a signal from a given sensor at a given depth. This study confirms the feasibility of monitoring fetal movements by the Actifetus system and demonstrates the importance of the characterization of fetal rhythms (and fetal behavior). The Actifetus system will serve as a new mean for studying fetal response to environment and detecting anomalies related to fetal suffering. (E-mail: ali.kribeche@med.univ-tours.fr)

Key Words: **Ultrasound, Pulsed Doppler, Fetal movements, Fetal monitoring, Autocorrelation function (ACF), Fast Fourier transform (FFT).**

INTRODUCTION

The motivation for monitoring the fetus through pregnancy is to recognize pathologic conditions, typically asphyxia, with sufficient warning to enable clinician intervention before the occurrence of irreversible changes. Fetal heart rate (FHR) is a major parameter for monitoring pregnancies and labor because it can be an indicator of acute fetal distress. The use of fetal biophysical profiles in high-risk pregnancies (gravidic hypertension, *in utero* infection, *etc.*) helps to distinguish healthy fetuses from those with chronic conditions. Parameters usually analyzed are fetal movement rate, fetal breathing movement (FBM) rate and amniotic fluid volume. However, the two first parameters are obtained by prolonged echographic observation, which is difficult to propose for routine survey of pregnancies.

Many systems and methods have been proposed to monitor FHR and fetal activity. One of the earliest attempts was made by Hammacher et al. (1968). The purpose of their method was to determine heart rate from the heart sounds. They also mentioned the detection of the heartbeat by using the R-wave of an electrocardiogram.

Timor-Tritsch et al. (1976) used a tocodynamometer to detect and study physiologic fetal movements. They defined four basic fetal movements in terms of duration, recorded patterns and descriptive terminologies for identifying each movement: they were high frequency movement (0.1 s to 0.4 s), respiratory movement

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(0.4 s to 1.2 s), mean duration movement (3 s) and rolling movement (14 s).

Melendez et al. (1992) used the HP-M-1350-A system to evaluate the ability of a commercially available monitor to record and discriminate between the movement of various fetal body parts. They showed that the fetal extremity movements were recorded accurately by that fetal monitor.

Lowery et al. (1995) developed an automated ultrasound-based fetal movement detection system using either a single (Russell 1) or a double transducer (Russell 2). The performances for movement detection were compared with those obtained with the HP-M-1350-A. The Russell 2 system had improved sensitivity without loss of specificity over the single-Doppler system. It proved to be a new noninvasive Doppler-based system for the evaluation of fetal well-being.

Murakami et al. (1992) developed an intelligent communication network for fetal monitoring (HOMIC network). Others systems of monitoring using piezoelectric sensors were developed by Sadovsky et al. (1977), Karlsson et al. (2000) and Yamakoshi et al. (1996).

The objective of our work was to develop a portable ultrasonic system able to detect the different fetal movements (whole body, chest, legs and heart) and to characterize them mainly in terms of quality (speed, amplitude, duration) to evaluate precisely the natural behavior of the fetus and its responses to stimuli. The electronic part of the ultrasonic device, called Actifetus (developed in cooperation with Ultrasons Technologies, Tours, France), is connected to a set of 12 ultrasonic Doppler sensors positioned on the maternal abdomen and covering the major part of the fetal structures. From the Actifetus system, it is possible to record the information needed to evaluate FHR, fetal breathing movement (FBM), limbs movements and global movements of the fetus. Maternal activity may be recorded in parallel using an accelerometer.

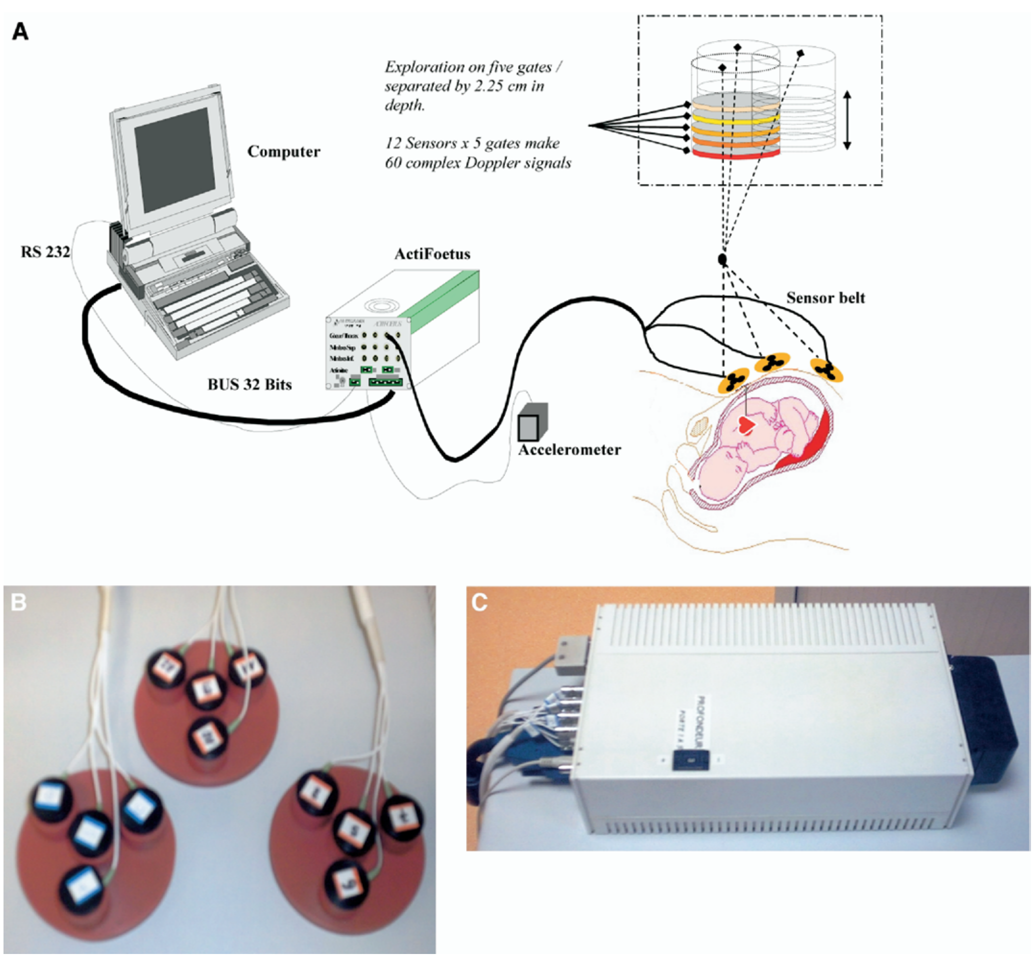

Fig. 1. (a) Actifetus set-up: 12 pulsed Doppler sensors are inserted in a flexible matrix and positioned on the maternal abdomen. They are linked to a pulsed Doppler system that detects the Doppler signals generated at five successive depths by fetal structure movements. The electronic module is connected to a laptop computer for signal storage and signal processing. (b) Ultrasonic sensor belt. (c) Doppler system multichannel (12 × 5 gates).

The Doppler signal generated by fetal movements is analyzed in three ways: (1) in terms of amplitude by separately plotting positive and negative components (separating from and toward transducers); (2) in terms of phase by unwrapping the phase of the reflected signals and (3) in terms of frequency shift by spectral analysis of Doppler signals.

MATERIALS AND METHODS

Ultrasonic sensor belt

A supple probe holder was built to maintain the transducers in fixed positions on the maternal abdomen during recording. The design of the sensor belt ensures that maternal movements will not cause the system to fail. It consists of a flexible matrix of polymer in which the sensors are positioned (Fig. 1b). It contains 12 separate ultrasonic transducers that detect fetal movements in a volume of approximately 20 $\times$ 20 $\times$ 15 cm^3. In accordance with the aim of increased patient comfort, possible future ambulatory use or fetal monitoring at home, the ultrasonic sensors were designed to be lightweight (20 g) and relatively small (diameter 20.4 mm).

The ultrasonic sensors are connected to an electronic multigate (five gates), pulsed Doppler device, operating at 2.25 MHz frequency (Fig. 1c). A group of four of the 12 sensors is positioned facing the thorax of the fetus for monitoring FHR, respiratory rate and whole-body movements. The other sensors are positioned for detecting movements of the limbs. B-mode examinations made before the recording session are used to determine the spatial location of the different parts of the fetus.

Experimental set-up

The Actifetus system (Fig. 1a) is composed of three electronic cards, each driving four ultrasonic probes and five different time windows corresponding to five successive exploration depths. A schematic view of the complete system is shown in Fig. 2. After quadrature demodulation, the signals from the sensors are filtered by a fourth-order analog bandpass filter. The lower-frequency threshold was chosen to be as low as possible while still eliminating low-frequency clutter, and the upper threshold was higher than Doppler frequencies expected from fetal structure movements. A laptop computer acquires the 120 low-frequency signals (12 $\times$ 5 gates make 60 complex Doppler signals) *via* an acquisition card at resolution of 32 bits.

The data are gathered on 12 bits and transmitted on 16 bits together with the indices of depth gate and sensor identification. Specific software has been developed for data processing and display. The Doppler frequency shift corresponding to fetal movements is displayed after frequency analysis. The amplitude of displacement of the internal tissue is estimated by using an arctangent method (the phase of the signal varies proportionally to the displacement of the reflecting target).

Signal processing

The echoes backscattered from the fetal structures are characterized by their amplitudes, which depend on of the scanning conditions and the nature of the reflecting structure, and by their phases, which depend on the location of the tissue. The received echo is thus both amplitude and phase modulated, which takes the following mathematical form

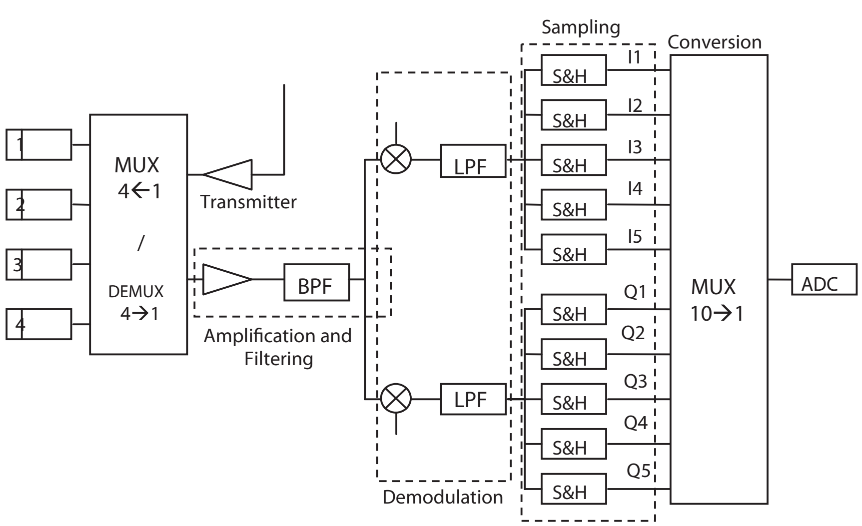

Fig. 2. Schematic view of one of the three electronic modules of the Actifetus system. After quadrature demodulation, the Doppler signal is filtered and sampled at time intervals corresponding to the five depth gates (see text for complementary information).

$$S(\tau) = A(\tau)\sin(2\pi F\tau + \phi(\tau)) \tag{1}$$

where S is a returned echo, A is the amplitude of the echo, F is the ultrasound transmission frequency, ϕ is the phase of the ultrasound echo and τ is the time. The value of τ is proportional to the depth X of the tissue whose scattering determines the amplitude $A(\tau)$ and phase $\phi(\tau)$

$$\tau = 2X/c \tag{2}$$

where c is the speed of sound in tissue ($\sim$1.5 mm/μs).

Equation (1) represents just one echo. For multiple transmit pulses, the received echoes are

$$S(\tau, kT) = A(\tau, kT)\sin(2\pi F\tau + \phi(\tau, kT)) \tag{3}$$

where T is the time between transmit pulses and k is an integer representing the pulse number.

The product kT is used to represent "slow" time, corresponding to the phase or displacement changes at a given depth across multiple pulse-echo cycles. "Slow" time is on the order of milliseconds or seconds. The received echo from a specific pulse-echo cycle (*i.e.*, a fixed value of k) can be base-banded to yield

$$S_b(\tau) = A(\tau)e^{j\phi(\tau)} = I(\tau) + jQ(\tau). \tag{4}$$

Note from eqn (4) that $I(\tau)$ and $Q(\tau)$ will be 90° out of phase, which is one quarter of one period of the ultrasound wave. $I(\tau)$ and $Q(\tau)$ are, therefore, referred to as the quadrature representation of the received echo

$$\phi(\tau) = \mathrm{atan}(Q(\tau)/I(\tau)) \tag{5}$$

For a fixed value of τ, corresponding to a specific depth location from the ultrasound transducer, the phase of the returned echo, $\phi(kT$, is directly proportional to the displacement of the tissue that produced the echo according to

$$X(kT) = (\lambda/2)((\phi(kT) - \phi_0)/2\pi) \tag{6}$$

where λ is the wavelength of the ultrasound in tissue and ϕ_o is the phase of the returned echo at the initial pulse-echo cycle. By sampling the base-banded quadrature signals, $I(\tau, kT)$ and $\phi(\tau, kT)$, in both "fast" time and "slow" time, displacements from multiple depth gates can be captured (Kanai et al. 1994; Shinozuka and Yamakoshi 1993).

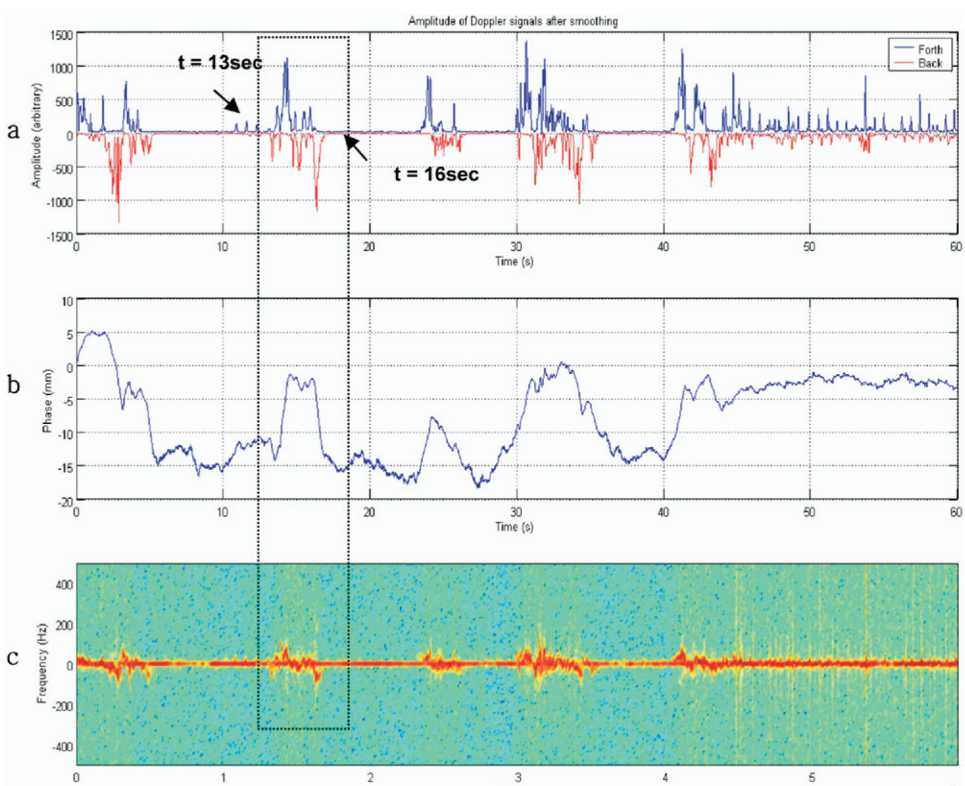

Fig. 3. Sixty-second recordings of signal reflected by fetal limbs positioned in a selected depth gate. (a) Amplitude of reflected signals (direction of movement is indicated by a color code). (b) Phase change of the reflected signals (amplitude of displacement). (c) Frequency analysis of Doppler signals (velocity of structure).

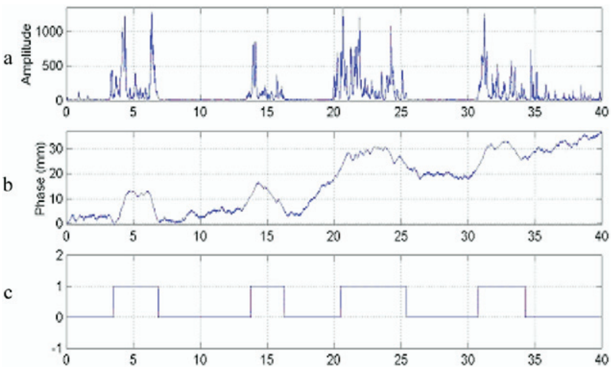

Fig. 4. Movements detection parameter (**0**, no movement; **1**, movement).

Frequency, phase and amplitude of reflected signals

The spectral analysis is a conventional method of analyzing a signal in the joint time–frequency domain. It provides the fast Fourier transform (FFT) of the signal *x(n)*, at the discrete time *n*, by computing the power spectrum of a small segment of the signal around *n*.

Movement detection algorithm

The fetus generates movements that, in general, cause an irregular package of peaks. We apply a detection algorithm based on the appropriate threshold to eliminate noise to isolate these packages. A movement was defined by an amplitude threshold slightly above noise level, a minimum duration of 0.1 s and a minimum rest duration of 0.5 s. A single movement is 0.1 s or more of movement (amplitude above the threshold) bounded by 0.5 s or more of nonmovement (amplitude under the threshold). For each movement, we defined two values: amplitude (maximum signal amplitude observed during the movement) and duration (time from the first sign of activity to the last for each individual movement).

FHR

The FHR was estimated by autocorrelation providing the beat-to-beat rate. The autocorrelation function (ACF) of a discrete signal x_i may be defined as

$$r_i(\tau) = \sum_{j=i+1}^{t+W} x_j x_{j+t} \tag{7}$$

where $r_i(\tau)$ is the ACF of lag τ calculated at time index t and W is the integration window size. The autocorrelation method compares the signal with its shifted self.

The ACF is the FFT of the power spectrum and can

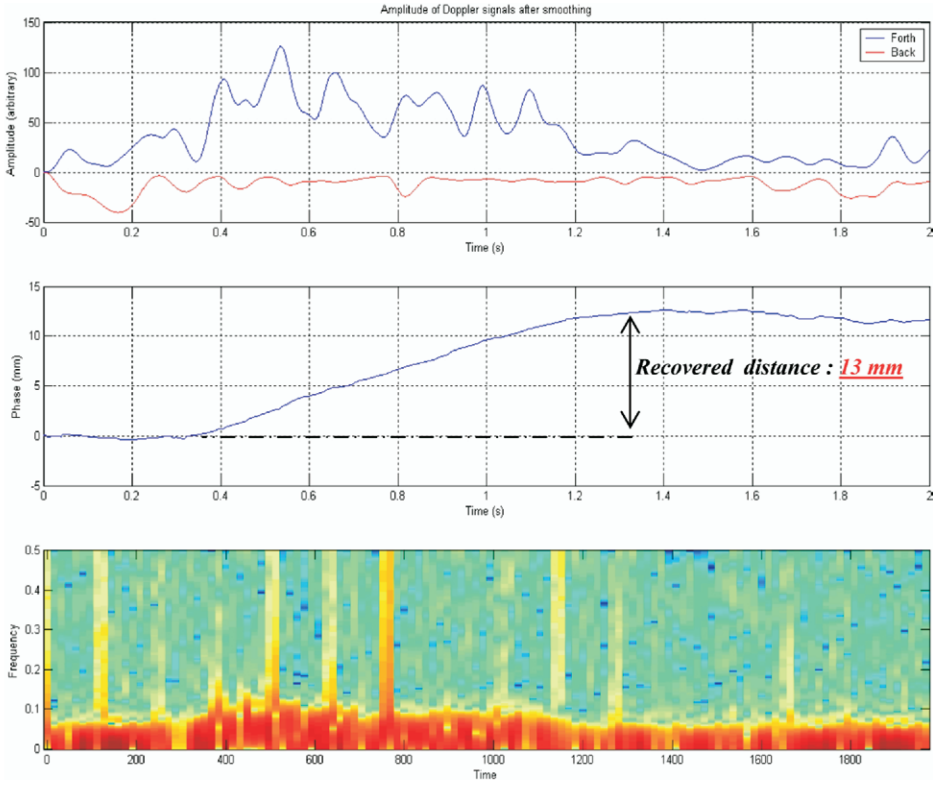

Fig. 5. Two-second recording of fetal kicking movement. From top to bottom: amplitude and direction (color code) of reflected signal distance of displacement, Doppler signal spectral analysis.

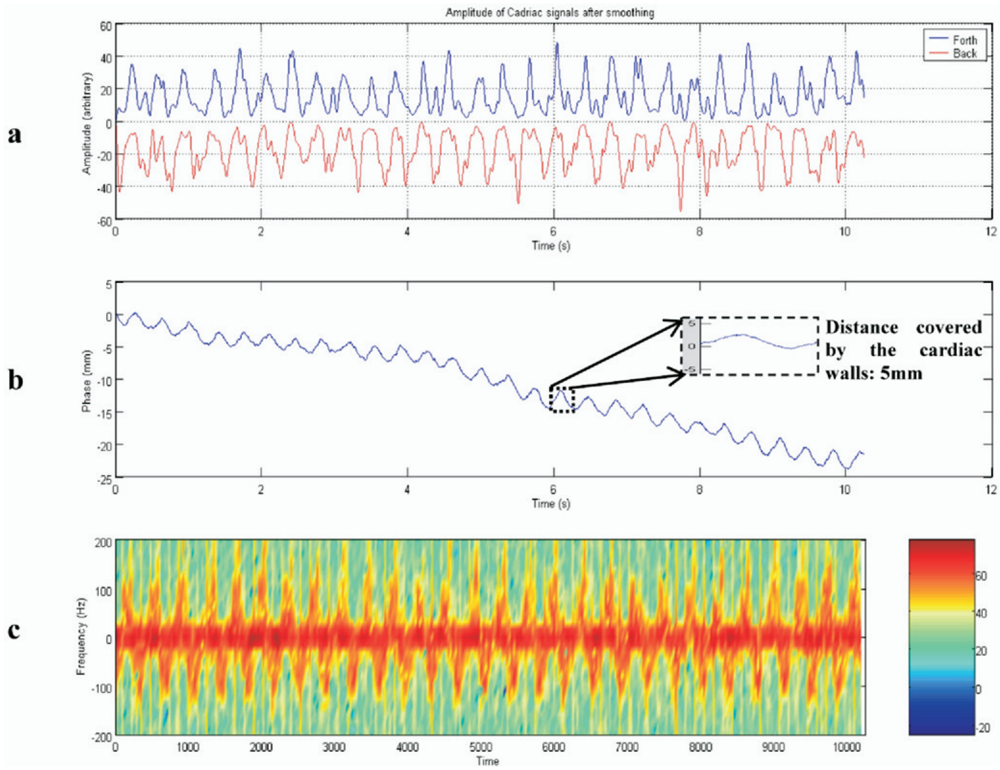

Fig. 6. Ten-second recording of signal reflected by fetal cardiac walls. From top to bottom: amplitude and direction (color code) of reflected signal distance of displacement, Doppler signal spectral analysis. The amplitude of cardiac structure displacement is in the range of 5 mm. It is associated with a slow global drift of the thorax.

be seen as measuring the regular spacing of harmonics within that spectrum.

To estimate the FHR, we applied the method suggested by Karlsson (1996). The algorithm developed and implemented in this study is composed of two modules: conditioning of the Doppler signal (smoothing of the signal using the autoconvolution function) and peak-to-peak detection of intervals between the successive beats (which represents intervals between two successive heartbeats). The FHR usually ranges between 90 and 200 beats/min.

Study population

This study was accepted by the local Ethics Committee. Each pregnant woman enrolled in the study was informed and gave personal agreement. Twelve pregnant women were examined between 30 and 36 weeks of pregnancy, in the Department of Nuclear Medicine and Ultrasound, University Hospital Bretonneau, Tours, France.

The recording of fetal activity was made immediately after a B-mode examination for routine follow-up of the pregnancy and localization of fetal structures. The recording duration was limited to a maximum of 20 min.

RESULTS

Tissue reflectivity, amplitude and direction of tissue displacement and tissue velocity

Fig. 3 shows an example of 60-s simultaneous tracings of Doppler signals arising from a selected depth gate of a captor facing the lower limbs of a fetus: (a) amplitudes of the reflected signals (positive signal corresponds to a movement that approaches the sensor and negative signal to a movement that moves away from the sensor); (b) phase of the signals (corresponding to the amplitude of displacement) and (c) spectral analysis (FFT) of Doppler signals. We can appreciate the appearance of several movements in an interval of 60 s.

Analyzing the three signals located in the interval (10 to 20 s): (a) at t = 13 s, the graph of amplitude shows that reflectors approach the sensor; (b) after a certain period of rest, at t = 16 s, the curve indicates that the reflectors move away from the sensor; (c) the signal of phase also shows an upwards displacement of around 10 mm of the limb starting at t = 3 s (when the phase is increasing, the Doppler frequency shift of the signal is positive) and (d) at t = 16 s, one can see the opposite,

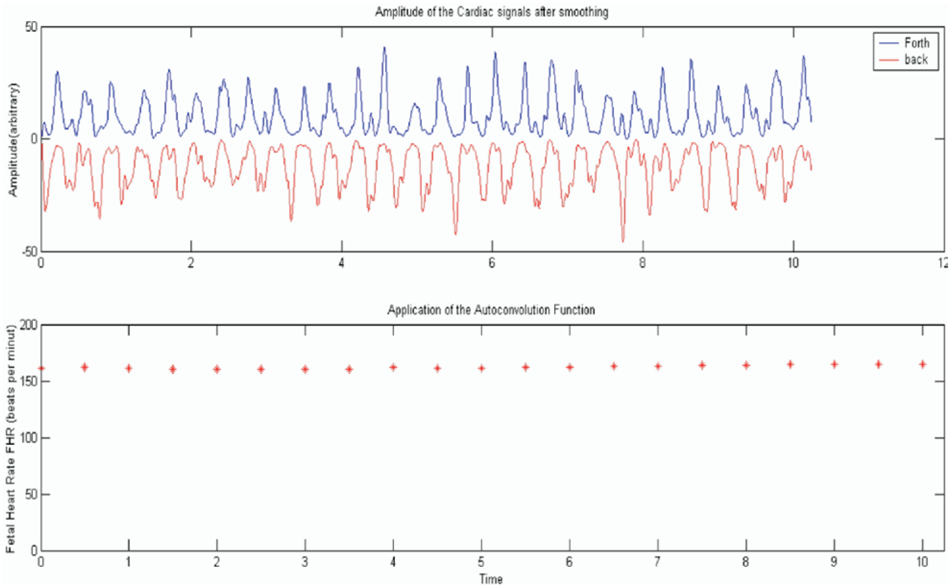

Fig. 7. Detection of the FHR using ACF. From top to bottom: amplitude and direction of the signal reflected by cardiac walls over a period of 10 s, graph of FHR detected by ACF (~160 beats/min).

i.e., a decreasing of the phase corresponding to a downwards displacement and a negative Doppler shift.

We then apply the movements detection algorithm on this signal. The amplitude signal with direction separation, plotted on Fig. 4, shows clearly the four movements. In Fig. 4c, the result of the movement detection algorithm application is shown. The algorithm succeeds in detecting the four movements (***0***, no movement; ***1***, movement).

Rapid extension–flexion movements of the legs are often associated with other fetal movements. A typical fetal kicking movement detected with the limb sensor is shown in Fig. 5. The kick accelerated steadily until it stopped abruptly as although it had hit the uterine wall. The return movement was slower. The total duration of the movements was about 2 s. The phase shift indicated that the length of the movement in the direction of the sensor was around 13 mm.

Fig. 6 shows example results from fetal heart signal processing. The amplitude curve shows a clear succession of positive and negative systolic and diastolic signals. The phase curve shows the expected back and forth displacement of cardiac structures with an amplitude of 5 mm, which is comparable with what is observed by M-mode ultrasound.

FHR

We used autocorrelation method for the estimation of FHR. Fig. 7 shows results of FHR calculation in a normal pregnancy, using the signal detected by one of the four sensors facing the fetal heart in depth gate 4. The FHR is about 155 beats/min, which agrees well with the values obtained when counting peaks on the spectrogram or on the phase graph.

Fig. 8 shows the results of FHR calculation when the algorithm is applied on the signals given by the 12 sensors at depth 4. In the signals of sensors 1, 2, 3, 4, 7 and 8, the software is able to detect the same heart rate as slightly higher than 156 beats/min, corresponding to the FHR. In the signals of sensor 12, the detected rhythm is lower than 100 beats/min and corresponds to the maternal heart rate. Data given by the other captors are relatively noisy and/or unstable because of the absence of a continuous, informative signal in the corresponding gate.

DISCUSSION

Until now, the means for noninvasive study of the behavior of the fetus in physiologic and pathologic conditions has been very limited. Therefore, except for FHR, very little is known concerning the "natural" rhythms of the fetus at different stages of its cerebral development (sleep/activity rhythm, coupling with the maternal rhythms, response to maternal stimuli, *etc.*). This information is mandatory for the evaluation of fetal well-being and the grades of fetal chronic conditions.

The major aim of the Actifetus system is to acquire information using a portable ultrasonic device that could be used in the clinic as well as at home for monitoring of pregnant women. The system is designed for possible miniaturization, to lead to a light battery-powered portable monitoring device. The signal and data processing could give real-time information on fetal behavior, which

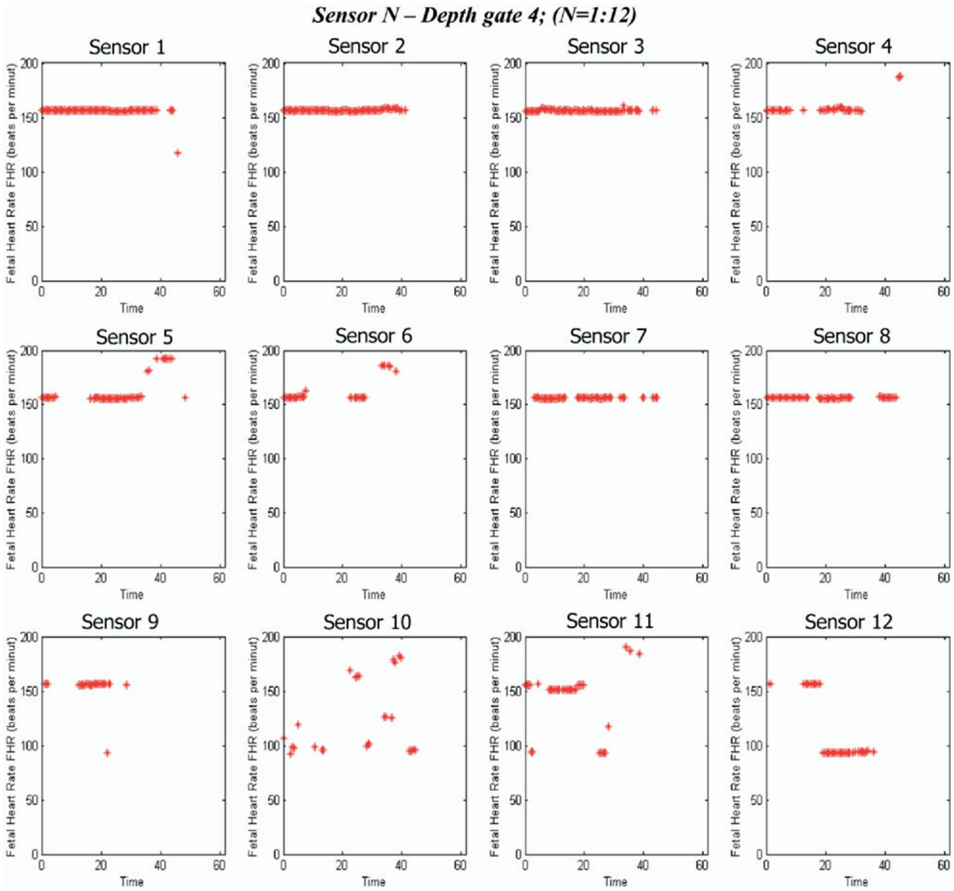

Fig. 8. Graphs of FHR in beats/min, computed by ACF during 40 s, from the signals detected at the same depth (gate 4) of each of the 12 ultrasonic sensors (for more information, please refer to the text).

will be either stored for further analysis or sent directly to a medical survey center.

The system is operating with 12 ultrasonic sensors and five depth gates, covering a total depth of 14 cm. The sensors are interrogated sequentially with low voltage levels (<10 V) so that the total ultrasonic energy transmitted to the fetus is less than that of a classic B-Doppler examination. For long-term monitoring of several hours, it would be necessary to acquire samples of a few seconds separated by sleeping periods so that the integrated duration of ultrasonic exposure will not exceed 20 to 30 min. We also tested the possibility of limiting the connections between the electronic device and the supple matrix supporting the sensors.

The information collected is complete enough for characterizing the different fetal movements in terms of amplitude, velocity, acceleration and synchronization. An important work is still necessary for obtaining precise data concerning what could be classified as "normal" or "pathologic" fetal behavior because the natural behavior and response to stimuli depends on cerebral maturation. The role of portable monitoring systems such as the Actifetus system could be of major importance for delivering information complementary to that obtained by sequential echography and Doppler examination of feto-maternal circulation.

CONCLUSIONS

We have shown that it is possible to develop a very sensitive ultrasound-based multigate multitransducer system for complete investigation of fetal movements, either rhythmic or episodic, and to characterize them in terms of amplitude and velocity. Several techniques of signal and data processing were used for extracting parameters that are complete enough for characterizing fetal rhythms (and allow the development of a complete fetal behaviour). The first results obtained in normal pregnancies are encouraging, and the next step in the work will be to develop a portable system for long-term monitoring of high-risk pregnancies in clinics and/or at home (telemedicine).

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