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● *Original Contribution*

胎儿活动系统:用于监测胎儿运动的多普勒传感器系统

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) © 2007 World Federation for Ultrasound in Medicine & Biology.

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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摘要 :胎儿心率(FHR)监测是高危妊娠和分娩监测的重要组成部分。其目的是发现任何可能表明急性胎儿窘迫和需要迅速治疗以避免死亡或包括脑障碍在内的严重后遗症等异常情况。在高危妊娠(妊娠高血压、子宫感染等)中使用胎儿生物物理特征有助于区分健康胎儿和那些患有慢性疾病的胎儿。胎儿生物物理特征评分已经被开发出来，集成了五个生物物理参数，其中一个是从FHR推导出来的。检测的主要参数是胎儿运动速度、胎儿张力、胎儿呼吸运动和羊水量。除FHR外，所有这些参数都是通过长时间的超声观察获得的，不能常规使用。在本研究中，我们开发了一种新的多门多换能器脉冲多普勒系统，用于胎儿行为的调查。利用快速傅里叶变换和自相关函数对胎儿运动产生的超声多普勒信号进行了处理和分析。胎儿结构运动所反映的信号幅度，胎儿结构位移(心、胸、四肢)的速度、方向和幅度。从这些参数可以计算FHR和表征胎儿活动。15名孕妇(30至36周)的初步体内结果非常令人鼓舞，但它们还有待于在未来的研究中得到证实。这些结果也证明了用于改进胎儿运动检测的传感器的优势。算法需要足够精确，才能让acti胎儿系统实时运行。我们现在有一些算法，可以成功地量化FHR和胎儿运动与信号从一个给定的传感器在给定的深度。这项研究证实了通过激活胎儿系统监测胎儿运动的可行性，并证明了胎儿节律特征(和胎儿行为)的重要性。该系统将成为研究胎儿对环境的反应和检测胎儿痛苦相关异常的新手段。(E-mail: ali.kribeche@med.univ-tours.fr)©2007世界超声医学与生物学联合会。

关键词:超声，脉冲多普勒，胎儿运动，胎儿监护，自相关函数，快速傅里叶变换

介绍

在妊娠期间监测胎儿的动机是识别病理情况，特别是窒息，在发生不可逆变化之前给予足够的警告，以便临床医生进行干预。胎儿心率(FHR)是监测妊娠和分娩的主要参数，因为它可以作为胎儿急性窘迫的指标。在高危妊娠(妊娠高血压、子宫感染等)中使用胎儿生物物理特征有助于区分健康胎儿和那些患有慢性疾病的胎儿。主要分析的参数有胎动率、呼吸运动(FBM)率和羊水量。然而，前两个参数是通过长时间的超声观察获得的，这很难在常规检查中提出。

许多系统和方法已被提出监测FHR和胎儿活动。最早的尝试之一是madebyhammacher等人(1968年)。他们的方法的目的是通过心音来确定心率。他们还提到了利用心电图的r波检测心跳。

用生育动力计检测和研究胎儿的生理运动。他们根据持续时间、记录模式和识别每个动作的描述性术语定义了四种胎儿基本动作:高频动作(0.1秒到0.4秒)、呼吸动作(0.4 s至1.2 s)、平均持续移动时间(3 s)和滚动移动时间(14 s)

使用HP-M-1350-A系统来评估商业上可用的监视器记录和区分胎儿身体不同部位运动的能力。结果显示，胎儿监护仪能准确记录胎儿的四肢运动。

开发了一种基于自动化超声的胎儿运动检测系统，使用单个(Russell 1)或双换能器(Russell 2)。运动检测的性能与HP-M-1350-A进行了比较。与单多普勒系统相比，Russell 2系统在不丧失特异性的情况下提高了灵敏度。这是一种新的基于多普勒的无创胎儿健康评估系统。

开发了胎儿监护智能通信网络(HOMIC网络)。其他使用压电传感器的监测系统由Sadovsky等人(1977)、Karlsson等人(2000)和Yamakoshi等人(1996)开发。

我们工作的目标是开发一个便携式超声系统能够检测到不同胎儿运动(全身、胸部、腿部和心脏),并描述他们主要在质量上(速度、振幅、持续时间)准确地评估胎儿的自然行为及其对刺激的反应。该超声波设备的电子部分被称为acti胎儿(与法国图尔的Ultrasons Technologies合作开发)，与一组位于母体腹部的12个超声多普勒传感器相连，覆盖了胎儿结构的主要部分。通过acti胎儿系统，可以记录评估胎儿FHR、胎儿呼吸运动(FBM)、四肢运动和胎儿整体运动所需的信息。母亲的活动可以用加速计并行记录。

(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.

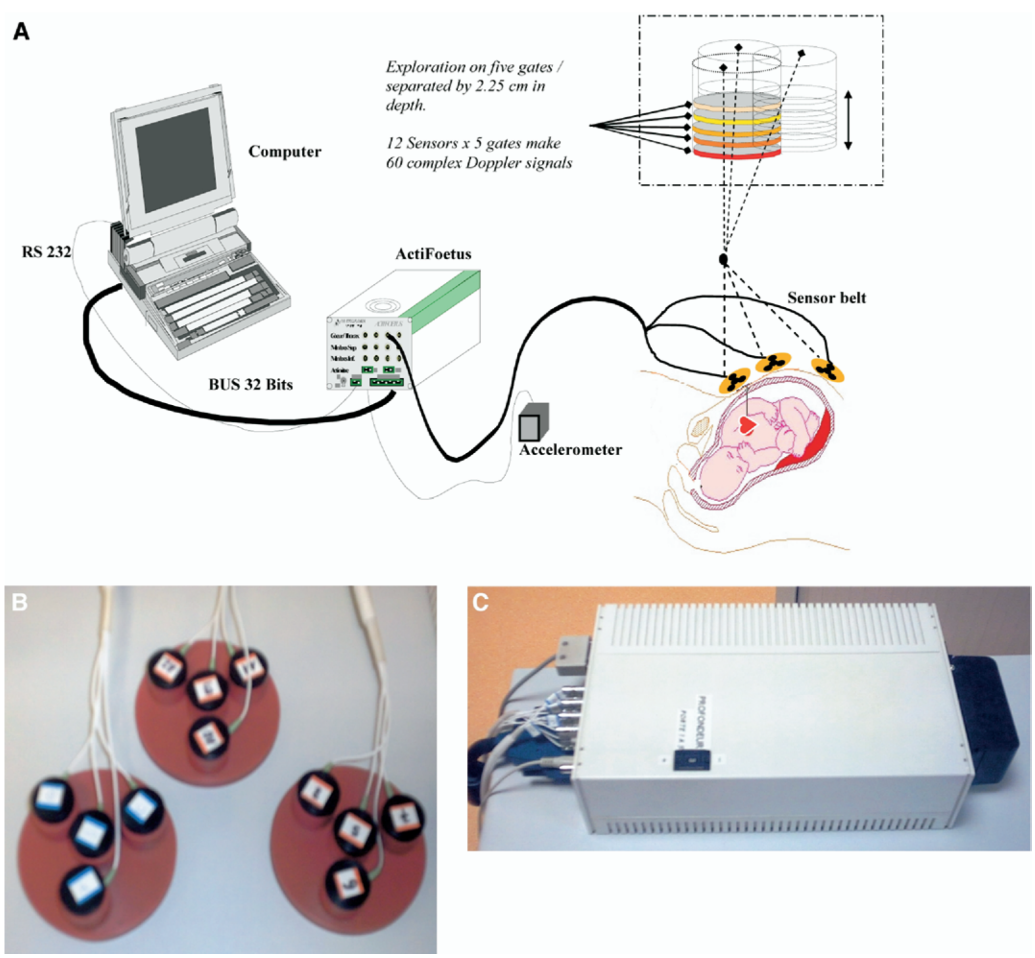


Fig. 1. (a) Actifetus set-up: 12 pulsed Doppler sensors are inserted in a flexible matrix and positioned on the maternal abdomen. They are linked to a pulsed Doppler system that detects the Doppler signals generated at five successive depths by fetal structure movements. The electronic module is connected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

图1所示。(a)胎儿活动装置:将12个脉冲多普勒传感器插入柔性基质并置于母体腹部。它们与一个脉冲多普勒系统相连，该系统可以检测由胎儿结构运动在五个连续深度产生的多普勒信号。该电子模块与笔记本电脑连接，用于信号存储和信号处理。(b)超声波传感器皮带。(c)多普勒系统多通道(12 ?5门)。

通过三种方法分析胎儿运动产生的多普勒信号:(1)分别绘制正分量和负分量(从传感器和向传感器分离)的振幅;(2)通过展开反射信号的相位来计算相位;(3)通过多普勒信号的频谱分析来计算频移。

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 × 20 × 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.

材料和方法

超声传感器带:在记录过程中，建立一个柔软的探头支架，以保持传感器在母体腹部的固定位置。传感带的设计确保了产妇的动作不会导致系统故障。它由一个柔性聚合物基体组成，传感器被放置在其中(图1b)。它包含12个独立的超声波换能器，在大约20*20*15立方厘米。为了提高患者舒适度，未来可能在家中使用或监测胎儿，超声传感器被设计为重量轻(20 g)和相对较小(直径20.4 mm)。超声波传感器连接到一个电子多门(五门)，脉冲多普勒设备，工作在2.25 MHz频率(图1c)。一组12个传感器中的4个面向胎儿的胸部，用于监测FHR、呼吸频率和全身运动。其他传感器的位置是用来探测四肢的运动。记录前的b型检查用于确定胎儿不同部位的空间位置。

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 × 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).

实验装置

acti胎儿系统(图1a)由三张电子卡片组成，每张卡片驱动四个超声探头和五个不同的时间窗口，分别对应五个连续的勘探深度。整个系统的示意图如图2所示。正交解调后，由四阶模拟带通滤波器对传感器信号进行滤波。在消除低频杂波的同时，尽量选择较低的低频阈值，上限阈值高于胎儿结构运动预期的多普勒频率。一台笔记本电脑获取120个低频信号(12 ?通过32位分辨率的采集卡，5个门产生60个复杂的多普勒信号。数据采集在12位，传输在16位，连同深度门指数和传感器识别。为数据处理和显示开发了专用软件。经频率分析显示胎儿运动对应的多普勒频移。内部组织的位移幅值是用反正切法估计的(信号的相位与反射目标的位移成正比)。

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

信号处理

胎儿结构的后向散射回波的特征是其振幅，这取决于扫描条件和反射结构的性质，以及其相位，这取决于组织的位置。因此，接收到的回波进行幅度和相位调制，其数学形式如下所示

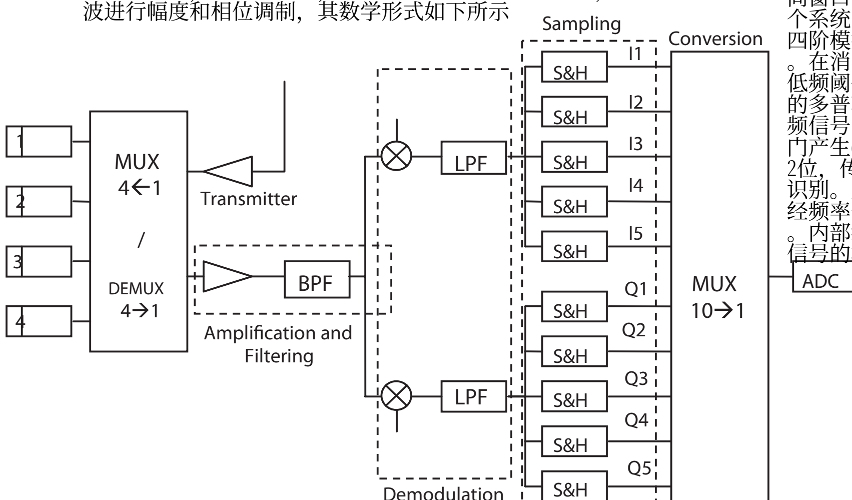


Fig. 2. Schematic view of one of the three electronic modules of the Actifetus system. After quadrature demodulation, the Doppler signal is filtered and sampled at time intervals corresponding to the five depth gates (see text for complementary information).

图2所示。acti胎儿系统的三个电子模块之一的示意图。在正交解调之后，多普勒信号被过滤并在与五个深度门相对应的时间间隔内采样(参见正文中的补充信息)。

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

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).

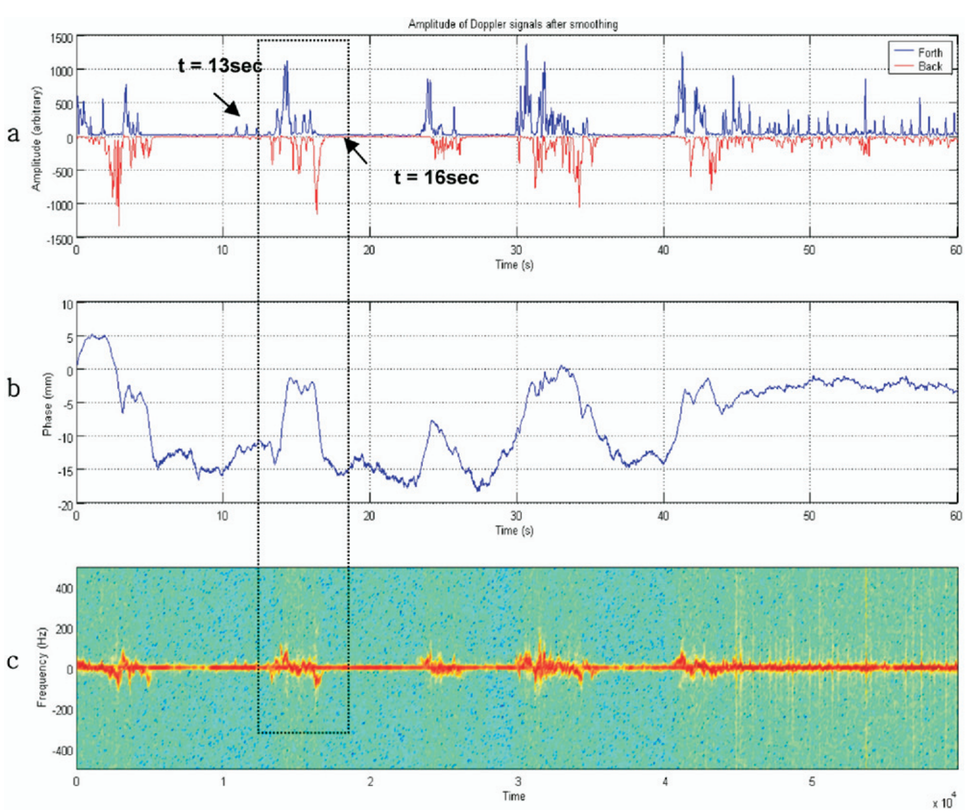


Fig. 3. Sixty-second recordings of signal reflected by fetal limbs positioned in a selected depth gate. (a) Amplitude of reflected signals (direction of movement is indicated by a color code). (b) Phase change of the reflected signals (amplitude of displacement). (c) Frequency analysis of Doppler signals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

六十二秒记录胎儿四肢在选定深度门的反射信号。(a)反射信号的振幅(运动方向用色标表示)。(b)反射信号的相位变化(位移幅度)。(c)多普勒信号频率分析(结构速度)。

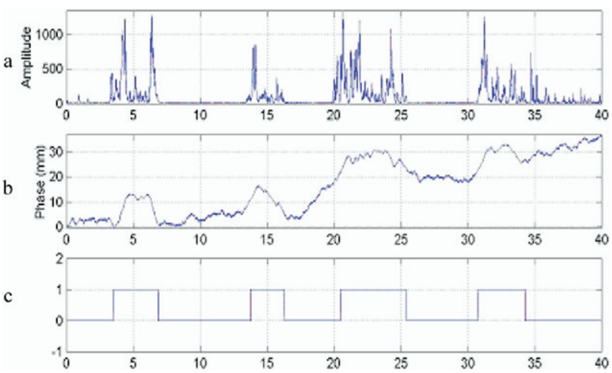


Fig. 4. Movements detection parameter (**0**, no movement; **1**, movement).图4所示。运动检测参数

反射信号的频率、相位和振幅

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.

频谱分析是一种常用的信号时频联合分析方法。它通过计算n附近一小段信号的功率谱，提供了信号x(n)在离散时间n处的快速傅里叶变换(FFT)。

Movement detection algorithm

运动检测算法

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).

胎儿产生的运动，通常会引起不规则的一系列高峰。我们采用一种基于适当阈值的检测算法来消除噪声，以隔离这些包。运动的幅度阈值略高于噪声水平，最小持续时间为0.1 s，最小休息时间为0.5 s。一个单一的运动是0.1 s或更长时间的运动(振幅高于阈值)和0.5 s或更长时间的静止(振幅低于阈值)。对于每个运动，我们定义了两个值:振幅(在运动期间观察到的最大信号幅度)和持续时间(从活动的第一个标志到每个独立运动的最后一个时间)。

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

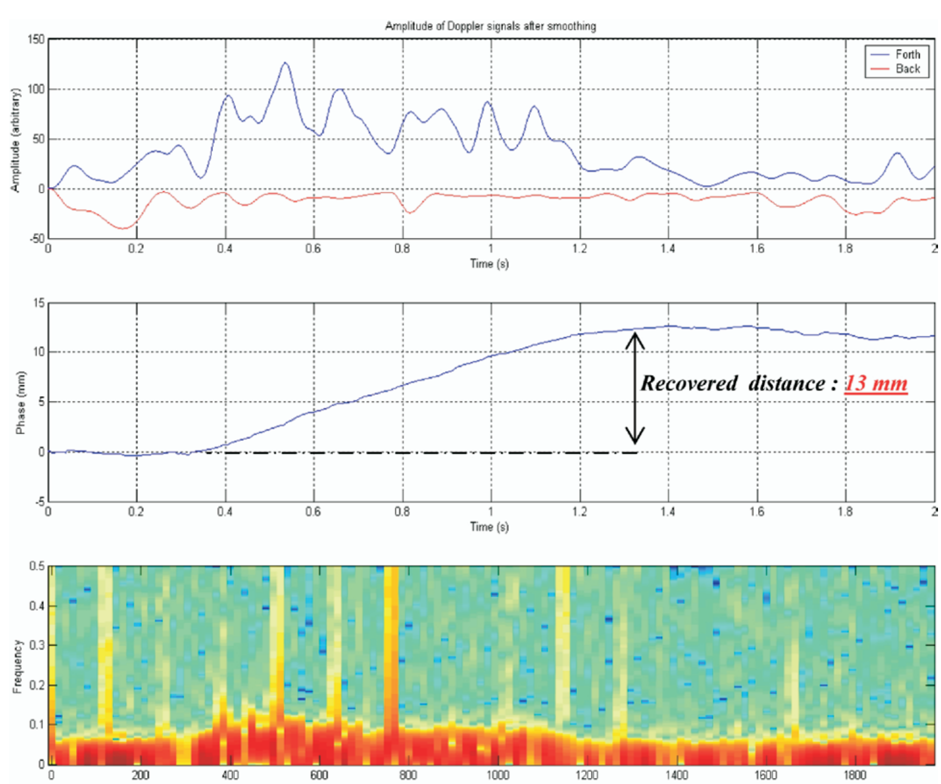
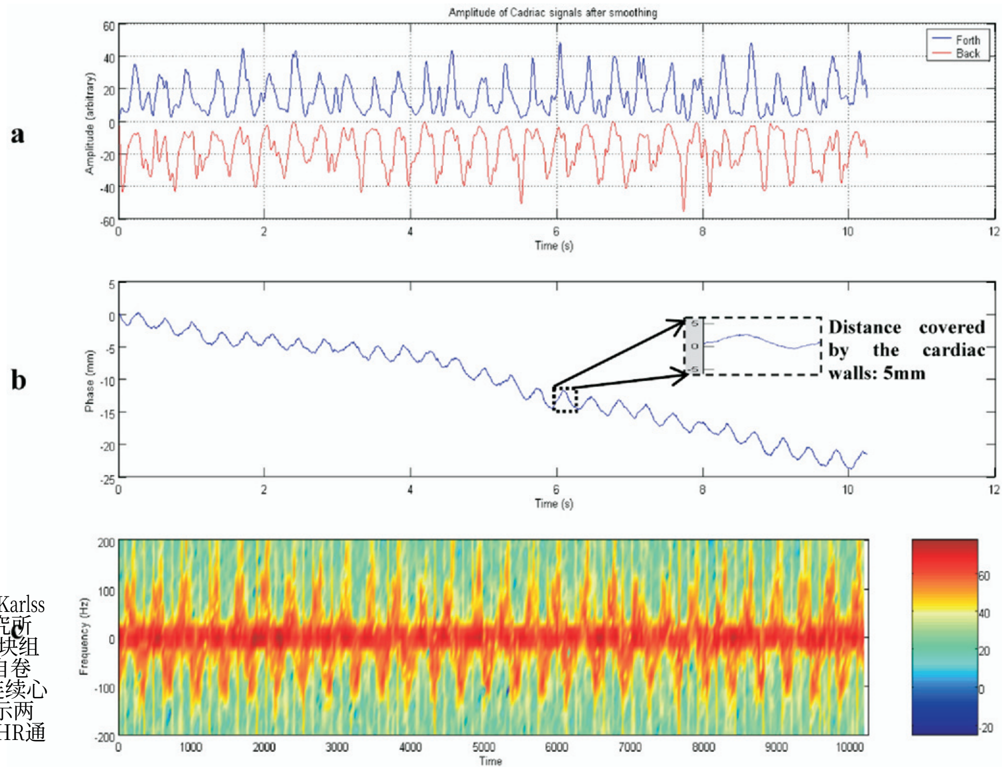


Fig. 5. Two-second recording of fetal kicking movement. From top to bottom: amplitude and direction (color code) of reflected signal distance of displacement, Doppler signal spectral analysis.

两秒钟胎儿踢腿动作的记录。从上到下:振幅和方向(色标)反射信号的位移距离，多普勒信号的频谱分析。



为了估计FHR，我们采用了Karlsson(1996)提出的方法。本研究所开发和实现的算法由两个模块组成:多普勒信号的调理(使用自卷积函数对信号进行平滑)和连续心跳之间间隔的峰-峰检测(表示两个连续心跳之间的间隔)。FHR通常在每分钟90到200次之间。

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.

胎儿心壁反射信号的10秒记录。从上到下:振幅和方向(色标)反射信号的位移距离，多普勒信号的频谱分析。心脏结构位移幅度在5mm范围内。它与胸部缓慢的全球漂移有关。

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.

研究人群
本研究被当地伦理委员会接受。每个参加研究的孕妇都被告知并给予个人同意。12名怀孕30至36周的孕妇在法国图尔布雷东诺大学医院核医学和超声科接受了检查。b型检查后立即记录胎儿活动情况，以进行常规妊娠随访和胎儿结构定位。记录时间限制在20分钟以内

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,

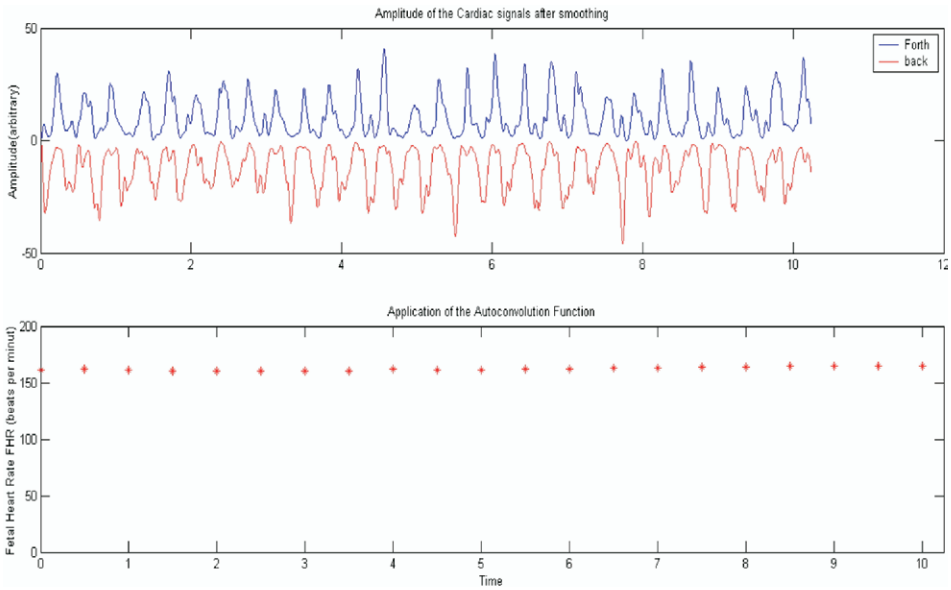


Fig. 7. Detection of the FHR using ACF. From top to bottom: amplitude and direction of the signal reflected by cardiac walls over a period of 10 s, graph of FHR detected by ACF (~160 beats/min).

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

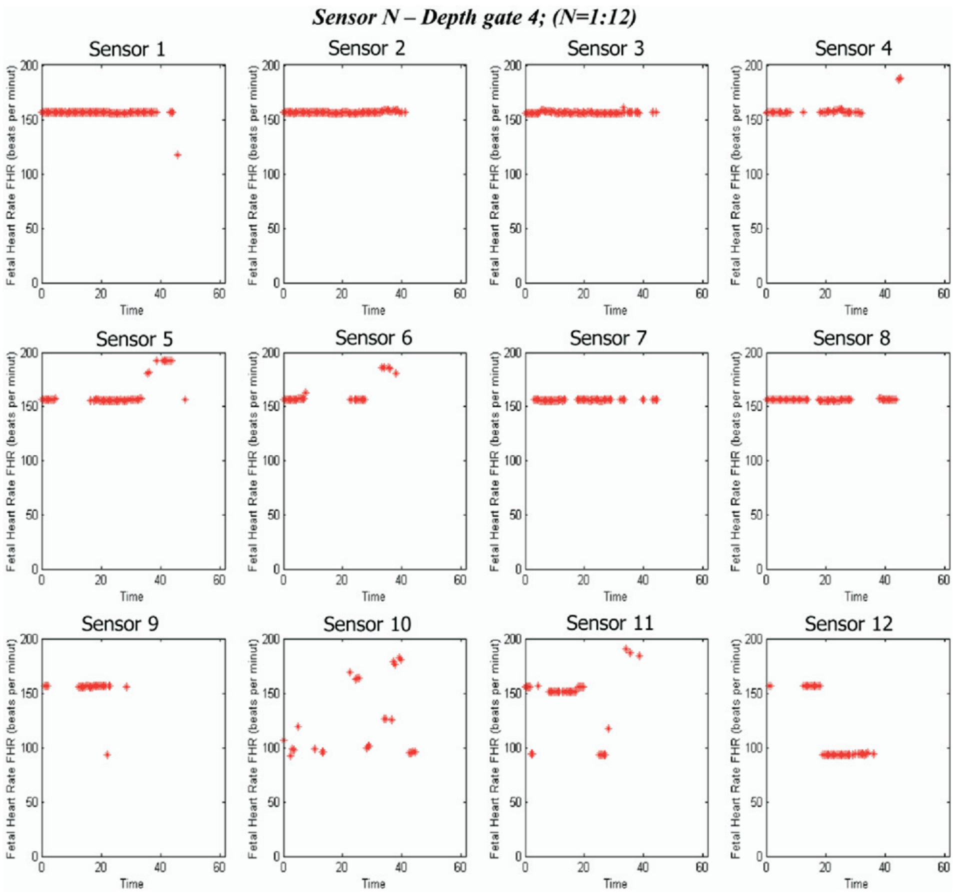


Fig. 8. Graphs of FHR in beats/min, computed by ACF during 40 s, from the signals detected at the same depth (gate 4) of each of the 12 ultrasonic sensors (for more information, please refer to the text).

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).

Acknowledgments—This work was supported by the Center Regional Council, the French Institute of Health and Medical Research

我们已经证明，开发一种非常灵敏的基于超声的多门多换能器系统是有可能的，它可以完整地研究胎儿的节律性或阵发性运动，并根据幅度和速度来描述它们。几种信号和数据处理技术被用于提取足够完整的参数来表征胎儿节律(并允许发育一个完整的胎儿行为)。在正常妊娠中获得的第一个结果是令人鼓舞的，下一步工作将是开发一个便携式系统，用于在诊所和/或在家里长期监测高危妊娠(远程医疗)。Acknowledgments-This工作

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