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Algorithm for Extraction of Fetal Heart Tones during Fetal Phonocardiography

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Abstract

The article describes the authors' algorithm for the extraction of systolic heart sounds during fetal phonocardiography. The algorithm is based on the assessment of the normalized average Shannon energy of registered signals. The algorithm is used to evaluate the fetal heart rate variability during the antenatal period of pregnancy. The article assesses the quality of the algorithm presented based on the analysis of fetal phonocardiograms acquired in the course of the physiological experiment.

Keywords

Acoustic signals; Shannon energy, Fetal phonocardiography; Heart rate; Heart rate variability

Introduction

Continuous control over pregnant women's state of health and intrauterine fetal development is a well-known problem of mother and child welfare. According to the official data, intrauterine fetal demise is observed approximately 10 times more frequently than sudden newborn death. At the same time, asphyxia (hypo-oxygenation) caused by different placental and/or maternal disorders leads to fetal death only in 60% of cases. Such a condition develops gradually and is accompanied with long-term fetal agony; therefore, there are a lot of opportunities to relieve this condition and guarantee successful delivery [1,2]. In this case, an ideal solution would be the development of a technique and corresponding tools to perform 24-h fetal monitoring similar to Holter monitoring in cardiology. However, this issue remains open for now.

Nowadays cardiotocography (CTG) is considered to be a common well-proven fetal health assessment technique. It is based on the assessment of the trends and dispersions of fetal cardiac contractions [2]. Under normal fetal development conditions, the fetal heart rate (FHR) varies constantly within specific limits, which is manifested as long-term periods of rapid and slow heart beats and changes in other parameters. Using periodic fetal monitoring during the antenatal period of pregnancy would allow reducing newborn disease incidence and intrauterine mortality in 2.5-3 times.

Existing FHR control methods do not allow performing long-term monitoring over the rhythmicity of fetal heart contractions without immobilizing the pregnant woman. Despite the fact that ultrasound techniques have a low-energy impact on the body, they cannot be considered absolutely safe, and the interval of impact is limited to 20-40 min. Until very recently, postponed interpretation of registered data has been used to acquire transabdominal fetal electrocardiograms (FECGs) by means of wearable fetal monitors. It is connected with the fact that the FECG amplitude is approximately 100 times smaller than that of common electrocardiograms, and it is registered against the background of high-amplitude noises caused by smooth muscles of the gastrointestinal tract (GIT) and urogenital organs as well as skeletal muscles. QRS complex detection and registration techniques have been developing for more than 30 years, but FECG processing still requires high-power computer systems and rather complicated processing algorithms [3]. Speaking about exotic CTG registration approaches, it is worth mentioning the radiofrequency microwave technique that allows registering the stroke volume periods as well as magnetocardiography [3]. The radiofrequency technique is based on the use of external energy impacts within the range of 12-15 GHz. The consequences of both these impacts and ultrasound methods in the fetus have not been studied completely yet, and the use of extremely low temperatures for the magnetocardiograph sensors does not allow implementing this method in the form of wearable devices [3].

Therefore, there is a long-standing need for developing a simple, convenient, noise-free passive technique for 24-h fetal development monitoring to be used outside of hospital settings. If the fetus's state of health deteriorates, nowadays high-risk patients are usually hospitalized for a long period of time, which implies considerable expenses. An alternative to this approach is the use of 24-h remote monitoring technologies that make provisions for achieving objective control over the fetal health.

Keeping in mind the principle of minimizing external effects on the developing fetus, passive, energy impact-free observation techniques should be considered to be the best options. FECG and fetal phonocardiography (FPCG) can be attributed to these techniques. The interest to FPCG reduced sharply following the introduction of precise and easy-to-use ultrasound techniques. It was connected with the imperfection of then-existing hardware facilities and impossibility of long-term registration of heart sounds by means of the stethoscope. If FPCG was implemented in the form of a wearable monitor with a wireless access to the server of a medical monitoring system, it would allow performing 24-h control over the fetus and pregnant woman's state of health, minimizing the period of time between fetal

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heath deterioration and notification of healthcare professionals and provision of medical care, reducing the number of pregnant women's hospitalizations for the purpose of health monitoring and, as a consequence, decreasing their hospital stay and treatment costs. Using a simplified version of this technique and corresponding device in home settings would allow performing out-of-hospital fetal monitoring and significantly reducing the risk of intrauterine fetal demise in out-of-hospital settings.

The group of authors set a goal to develop a simple and effective method for the extraction of fetal cardiac sounds against background noises on the basis of calculating Shannon free energy on fetal phonocardiograms (FPCGs) during the antenatal period of development. Another goal was the development of an acoustic sensor and prototype for the registration of fetal heart tones in order to calibrate this technique on real-life signals acquired in the course of the physiological experiment. The latter goal is not reviewed in this article.

Materials and Methods

The key problem of implementing the FPCG technique is the detection of heart sounds with reference to every systolic cycle of heartbeats and further processing of these signals. The noise contamination of FPCG signals is conditional to the following reasons [4-6]:

- FPCG signals depend on the fetal presentation;
- fetal movements cause acoustic noises typical of specifically its movement activity (which can be used as a corresponding marker);
- pregnant woman's GIT sounds can overlay FPCG signals;
- FPCGs contain pregnant woman's cardiac sounds;
- FPCGs contain pregnant woman's respiratory sounds; and
- FPCGs contain external noises.

The early research activities were primarily focused on the development of noise-resistant sensors and conduction of various time-and-frequency analyses of signals. Recent activities have been focused on the development of reliable signal extraction algorithms [7]. However, in any case, FPCG processing implies mandatory filtration of external noises and human body noises. Various hardware passband filters or filtration algorithms are used for this purpose such as frequency-domain threshold filtering, homomorphic and median filtering, and filters with different parameters [8]. Filtered signals undergo further processing in order to search for and detect specific FPCG fragments relevant to heart tones. However, scientific literature still contains no detailed quantitative assessments of the performance of well-known processing techniques, and the reliability of acquired findings leaves much to be desired [9-12].

The article presented describes the registration of fetal heart tones by means of the prototype monitor. The general functional design of the monitor is presented in Figure 1.

FPCG signals were detected by a piezoelectric sensor placed on pregnant women's front abdominal wall, at the place of the best point of auscultation for fetal heart sounds. The sensor was developed and produced on the basis of a piezoelectric converter. The signals detected by the piezoelectric sensor were amplified by an electrometric amplifier with the noise level of 8 nV/√Hz and transferred to an active fourth-order passband filter with adjustable cutoff frequencies. The filtered signals were transferred to the audio input of a laptop audio card. The audio card was based on a high-speed 24-digit analog-to-digital converter. Then the signals were recorded on the hard disk drive.

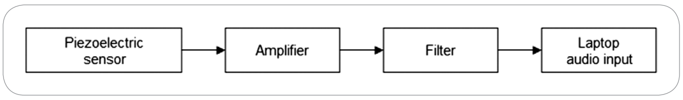

Figure 1: General functional design of the prototype monitor

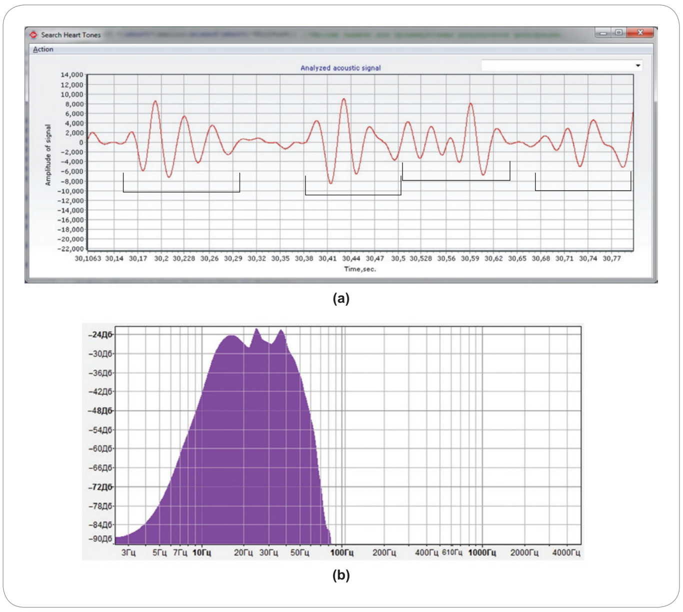

Figure 2: FPCG fragment: A – fragment of the acquired acoustic signal; B – spectrogram of the acoustic signal

Recording was performed by means of the free sound editor Audacity 2.0.5 under Windows 7; the signals were recorded in the form of WAVE files (16 bits, sample frequency of 10,000 Hz).

During the research, the authors tried several approaches to the search and identification of heart sounds. In their opinion, the modified calculation of free Shannon energy appeared to be the most promising option. This technique allowed the extraction of fetal heart tones [13]. At the first stage, signal preprocessing was performed (the second-order Savitzky-Golay filter, fourth-order Butterworth filter, and median filter with a varying window width were approved) in order to eliminate noises. Before calculating Shannon energy, input signals (1) were normalized to level heart sounds S by amplitude

$$x_{\text{norm}}(t) = \left(\frac{x(t)}{\max(|x(t)|)} \right). \qquad (1)$$

The algorithm for the extraction of fetal cardiac tones was based on the condition that they were represented by low frequencies, and overlaid noises were represented by high frequencies. The FPCG fragment (Figure 2A) and its spectrum (Figure 2B) are represented below. Figure 2A demonstrates the extracted systolic heart tones coinciding with auscultation findings.

The signals with the frequency of lower than 60 Hz and high amplitude correspond to fetal systolic heart tones. In this connection, the authors used a low-frequency software filter with the cutoff frequency of 50 Hz to preprocess the signals and eliminate external noises. The FPCG envelope was built in order to detect the starting

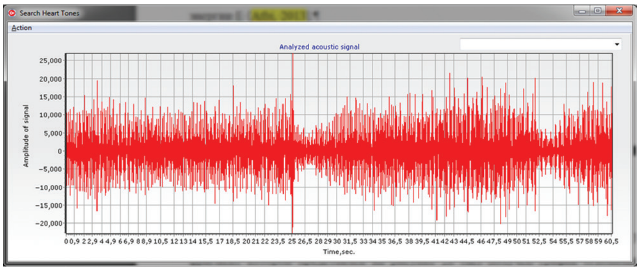

Figure 3: FPCG under study

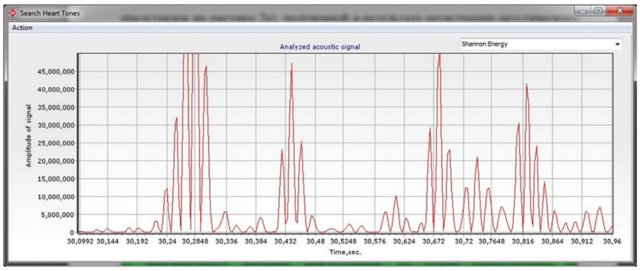

Figure 4: Envelope of the normalized average Shannon energy

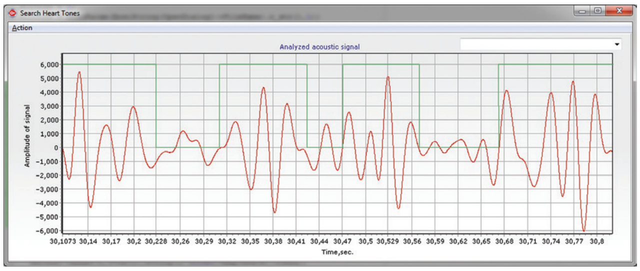

Figure 5: Output of the algorithm in terms of the detection of FPCG systole time intervals. Square-wave signal – changes in Parameter *T*3. Time intervals *T*3 = 1 coincide with the systole time intervals

point of heart sounds. Shannon energy (E) was calculated according to the following formula (2)

$$E = -S^2(t)\log(S^2(t)), \qquad (2)$$

where $S(t)$ – input signal, and the normalized average Shannon energy was calculated from the formula

$$E_m = \frac{E - \bar{E}}{\sigma_E}, \qquad (3)$$

where $\bar{E}$ – normalized average energy E, σ_E – mean-square deviation of energy E [13].

The calculation of the normalized average Shannon energy of FPCG (Figure 3), the fragment of which was demonstrated in Figure 2A, allowed building the envelope of the energy under study (Figure 4).

FPCG (Figure 3) was acquired by means of the prototype monitor developed by the authors, from the pregnant woman's abdominal surface in pregnancy week 29.

Following the calculation of the normalized average Shannon energy of FPCG, the acquired data underwent median and threshold filtering, and nearby energy impulses corresponding to one and the same heartbeat were united. In order to unite nearby energy impulses, the authors used their experimental research findings. These experimental research findings were based on the observations showing that the pause between heartbeats varied depending on the cardiovascular parameters of the fetus. However, when uniting nearby energy impulses (calculation data of the normalized average Shannon energy), one can follow the next principle: if the extremes of energy impulses are observed within 50 msec from each other, they belong to one and the same heartbeat. Single energy impulses with the time length of less than 300 msec were excluded from the data set under study during the further search for fetal heart contractions. Figure 5 demonstrates the output of the above-described algorithm in terms of the extraction of heart tones from the FPCG fragment under study.

In order to detect the systolic time intervals, the authors used an original adaptive threshold algorithm. Threshold values of the normalized average Shannon energy were calculated in conformity with the statistical parameters of signals within a limited time interval. It allowed the significant improvement of the noise immunity of the systolic time interval detection since the noises registered had an impact only during a limited period of time. The starting point of systole T1 was chosen as a percentage ratio out of the maximum value of the envelopegram. It depended on the root-mean-square value of several preceding peaks of free Shannon energy. The same method was used to choose the end point of systole T2 based on the parameters of previously detected heart tone intervals. Trigger parameter T3 was introduced in order to detect FPCG systole time intervals. The value of this parameter versus the normalized average Shannon energy was changed according to the following law:

$$\begin{cases} T1 \le T2, \\ T3 = 1\big|_{E_m > T1}, \\ T3 = 0\big|_{E_m < T2}. \end{cases} \qquad (4)$$

Figure 5 demonstrates the output of the algorithm in terms of the detection of FPCG systole time intervals. Trigger parameter *T*3 curve is laid over the FPCG curve. The values of the *T*3 curve change from 0 to 1. If *T*3 is equal to 1, these time intervals are considered to be the FPCG systole time intervals.

Results and Discussion

The proposed algorithm for the extraction of FPCG systole tones demonstrated good stability and high specificity for the detection of systole time intervals in model and real-life FPCG signals and in the presence of pathological noises during the systolic phase.

Detecting FPCG systole time intervals by means of the assessment of free Shannon energy allowed performing this procedure not only at the laboratory of functional diagnostics but also against the background of interferences and noises of the clinical ward. This technique allowed simplifying and, in some cases, abandoning the preliminary processing of signals, in particular, high-frequency noise filtering. It was achieved due to the optimization of the algorithm by choosing threshold limit value *T*2 that differentiated accidental free energy impulses caused by background noises and high-amplitude determined changes in the level of energy in synchrony with heart tones.

Speaking about the well-known findings of perinatal phonocardiography, the signals of heart tones were extracted by means of different versions of the frequency-domain analysis. As compared to these techniques, when analyzing real-life signals, the proposed method demonstrated higher stability and specificity and lower sensitivity to external interferences and pathological noises. Besides, additional use of certain parameters of the initial signal and free Shannon energy will allow developing a more effective algorithm for automatic detection of systolic heart tones in order to work with signals characterized by low ratio of signal/noise values.

Conclusion

The current algorithm for the detection of FPCG systole time intervals was implemented in the form of a software package for the hardware and software system for fetal and maternal health monitoring within the second and third trimesters of pregnancy. The FPCG processing and analysis allow creating objective and highly authentic fetal cardiotocograms. The passive monitoring technique eliminates restrictions to the duration of the procedure and makes provisions for 24-h continuous real-time observation. Using the simplest expert system and capabilities of 3G/4G wireless digital networks allows minimizing the risk of adverse and life-threatening conditions, simplifying medical caregivers' work, reducing their workload, and increasing their productivity.

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