

*fetal monitoring, fetal abdominal,
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COMPUTERIZED FETAL MONITORING BASED ON BIOELECTRIC SIGNALS FROM MATERNAL ABDOMEN

The paper presents an instrumentation set for effective diagnostics of early symptoms of fetal distress in high-risk pregnancy based on bioelectric signals recording. The representative database of records has been established that enabled the complex analysis of signals recorded on a surface of maternal abdomen. As an outcome, the effective algorithms have been developed for processing both the fetal electrocardiogram and the signal of electrical activity of a uterine muscle. This allowed the development of unique diagnostic system based on external biosignal measurement module connected to the standard personal computer. In this system, like in a classical fetal monitor, the fetal heart rate (FHR) signal together with contraction activity signal of uterine muscle and fetal movement become an essential source of information on fetal condition. In addition, there is a possibility for spectral analysis of FHR signal as well as a morphology assessment of fetal ECG signal.

1. INTRODUCTION

The aim of fetal monitoring is the prognosis and detection of intrauterine ischemia. The most effective method is a measurement of oxygen saturation of blood. Unfortunately, it is impossible because during a pregnancy we can't directly have access to fetus. Another way for detecting symptoms of hypoxia is monitoring of the central nervous system. It can be performed only by measurement of substitute parameter e.g. activity of fetal heart. At present, the basic method of monitoring the condition of unborn baby is the cardiotocography. Cardiotocographic monitoring relies on simultaneous recording of fetal heart rate (FHR) at the background of contractions of uterine muscle and fetal movement activity [5]. Detailed cardiotocogram analysis allows the obstetrician to take a decision on the delivery of pregnancy or the application of invasive labour procedures. It is intriguing why both in the monitoring of fetal heart activity and contraction activity during pregnancy and labour the mechanical methods are still used exclusively, i.e. ultrasound Doppler method [6] and an external tocography [3]. The undoubted advantage of these methods is simplicity and non-invasiveness. At the same time, in the general feeling an awareness exists that these methods are very subjective, less accurate and do not deliver a credible information on functioning of the examined organs. These disadvantages result exactly from indirect measuring technique that records only the effects of electric excitation – fetal heart movement and mechanical contractions of uterus. Considerably more comprehensive information for early recognition of

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disorder of central nervous system or for detection of premature labour risk can be obtained by recording primary bioelectric signals: fetal electrocardiogram – FECG (Fig.1) and electrohysterogram as an electrical activity of uterine muscle – EHG (Fig.2).

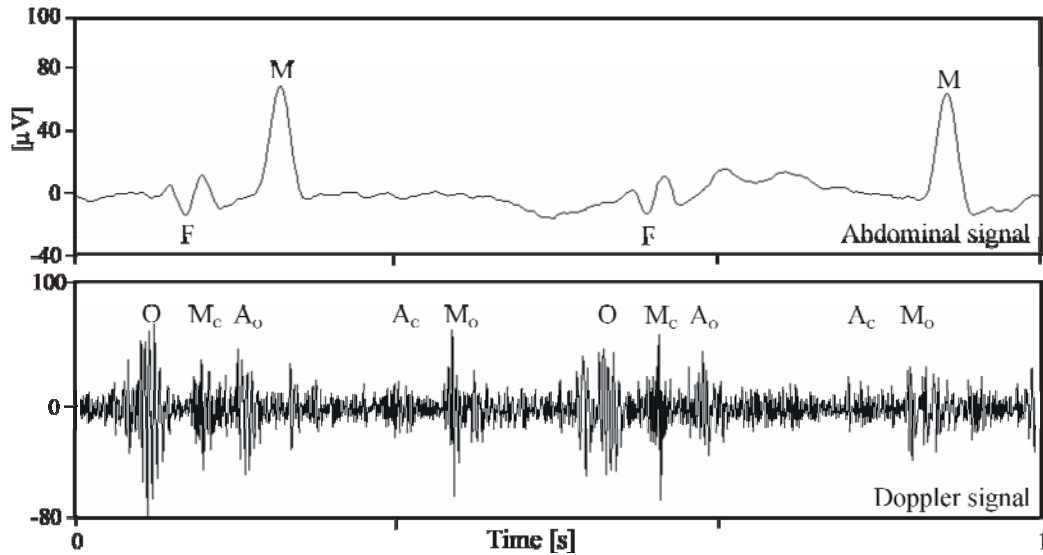


Fig.1. Signal of mechanical and electrical activity of fetal heart recorded simultaneously from maternal abdominal wall. F – fetal QRS complex with amplitude of order $1\div 50 \mu\text{V}$, M – maternal QRS complex with amplitude of order $0.1\div 1 \text{ mV}$, M_c and M_o – atrioventricular valve closure and opening, A_c and A_o – semilunar valve closure and opening, O – atrial activity.

Two methods of fetal electrocardiogram recording are being distinguished: direct and indirect. The direct method consists in electrocardiogram recording by means of scalp electrode placed on fetal presenting head. Invasiveness of the method and restriction of its use exclusively to labour period causes its rare application. Indirect electrocardiography, like the recording of electrical activity of maternal uterine muscle, relies upon recording of potentials with the use of electrodes placed on abdominal wall of pregnant woman. Indirect method is completely non-invasive and can be used in practice since the 12th week of gestation. [5].

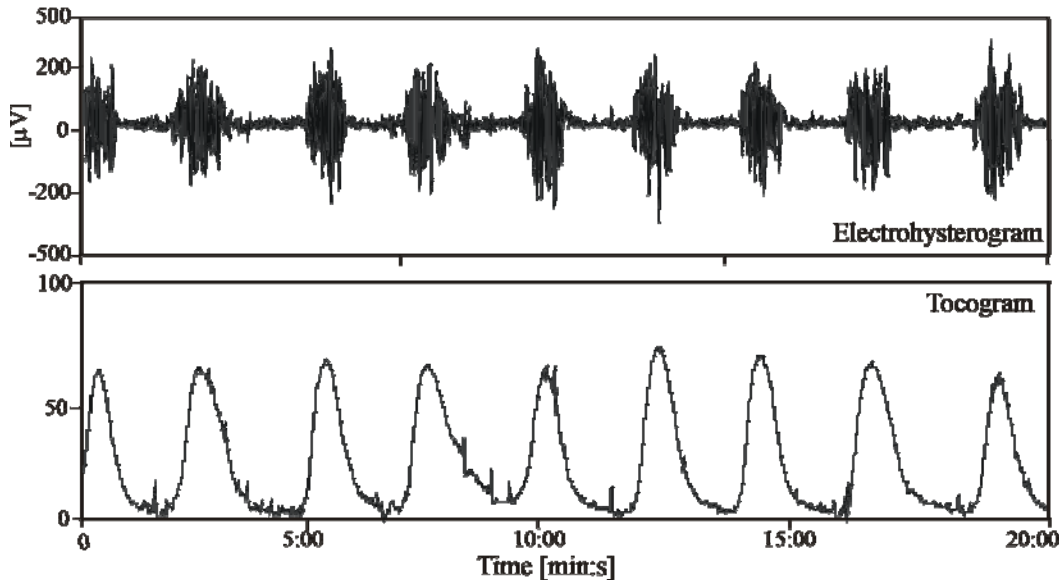


Fig.2. Simultaneously recorded signals of electrical and mechanical contraction activity of uterine muscle.

Indirect recording of electric activity of both the fetal heart and the uterine muscle is known long before now. The problems with measurement and analysis of signals in the presence of usually strong interference – interfering maternal electrocardiogram and muscular artefacts (see Fig.1) – have made impossible the application of this recording as a widespread diagnostic method. Continuous technical progress and common accessibility of computer-aided signal processing caused the renewed visible increase of interest in these methods [1], [2], [3], [7]. Apart from a higher diagnostic value, these methods show also substantial economic advantages.

2. INSTRUMENTATION

Figure 3 presents the block diagram of a system for acquisition and analysis of bioelectric signals being recorded on maternal abdomen surface. The system generally consists of two separate parts: the recorder of bioelectric signals and external computer. Recording circuit in a form of external, optically isolated module enables both the fetal ECG signal acquisition and electrical contraction activity by using the same signals being recorded on maternal abdomen surface. This module allows replacement of the expensive cardiotocographic instrumentation and ensures the higher diagnostic capacity at the same time. In addition, the reduction to a minimum number of applied leads makes it easy-to-use for the mother and medical staff.

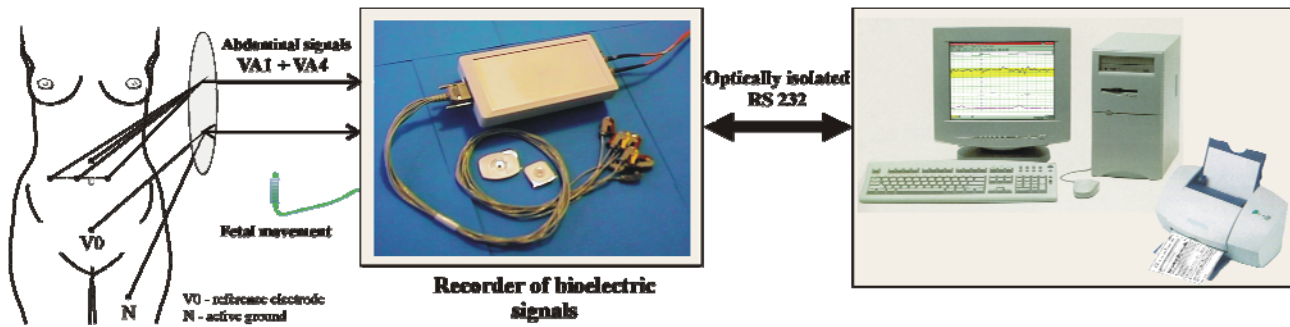


Fig.3. System for recording and analysis of bioelectric signals from maternal abdominal wall.

2.1. RECORDING HARDWARE

The recorder allows the acquisition of four abdominal signals which monitoring the electrical activity of fetal heart as well as electrical activity of uterine muscle. These signals are necessary for the correct assessment the state of unborn baby. The basic merits of the presented recording module are very low level of its own noise which does not exceed $0.5 \mu\text{V}$ (peak-to-peak) measured with reference to input (RTI) and large value of CMMR coefficient (120 dB) that ensures the proper suppression of mains interference. These parameters have been obtained thanks to non-typical recorder structure including complete separation of analog part from a digital part (separate printed circuit boards – PCBs, see Fig.4). In each of the four measuring channels, two preliminary amplifiers are used having constant gain equal to 20 and 25 V/V respectively that have been separated by the DC-component cut-off circuit. The next are band-pass filters and end amplifiers with adjustable gain in the range of 1 to 255 V/V. Entire circuit allows the amplification of recorded signals from the tens of microvolts up to a few volts level. Gain adjustment prevents the reaching of saturation state by the amplifiers in case of strong isoline drift. Moreover, the band-pass filters allows the change of lower cut-off frequency from 0.05 Hz to 1 Hz, thus also securing the circuit against too large low-frequency interference.

Selection of proper gain and cut-off frequency of filters can be done by a user via the computer at the beginning of monitoring taking into account the visual assessment of abdominal signals recorded. High cut-off frequency of filters is stable and equals 150 Hz, hence at the sampling frequency of 500 Hz, the recorder circuit is fully protected against a possibility of aliasing occurrence. There has been provided an additional outfit of the recorder: the module for recording a fetal movement activity being signalled by mother, the circuit for checking a skin-electrode connection and the low battery check circuit. Suitable information is sent to computer where it is displayed on a monitor screen in a form of graphical markers.

The digital part contains 16-bit microcontroller, A/D converter and a relevant set of keys for adjustment of gain and cut-off frequencies of filters. A task of microcontroller is to control the operation of entire circuit and communication with external computer. This communication takes place via a serial port and fiber-optic link. Application of the fiber-optic link and battery supply of the recorder ensures full safety of a mother and her baby during measurement. As it can be noticed in the block diagram, the control of keys takes place exclusively in the digital part, whereas their power supply is connected to the analog part which is provided with additional voltage stabilizer. This prevents from eventual interference appearing in the analog part during the gain adjustment

and changing the frequency of filters. Due to the same reason, the reference voltage (V_{REF}) of analog-to-digital converter is also drawn from analog part, not the digital one.

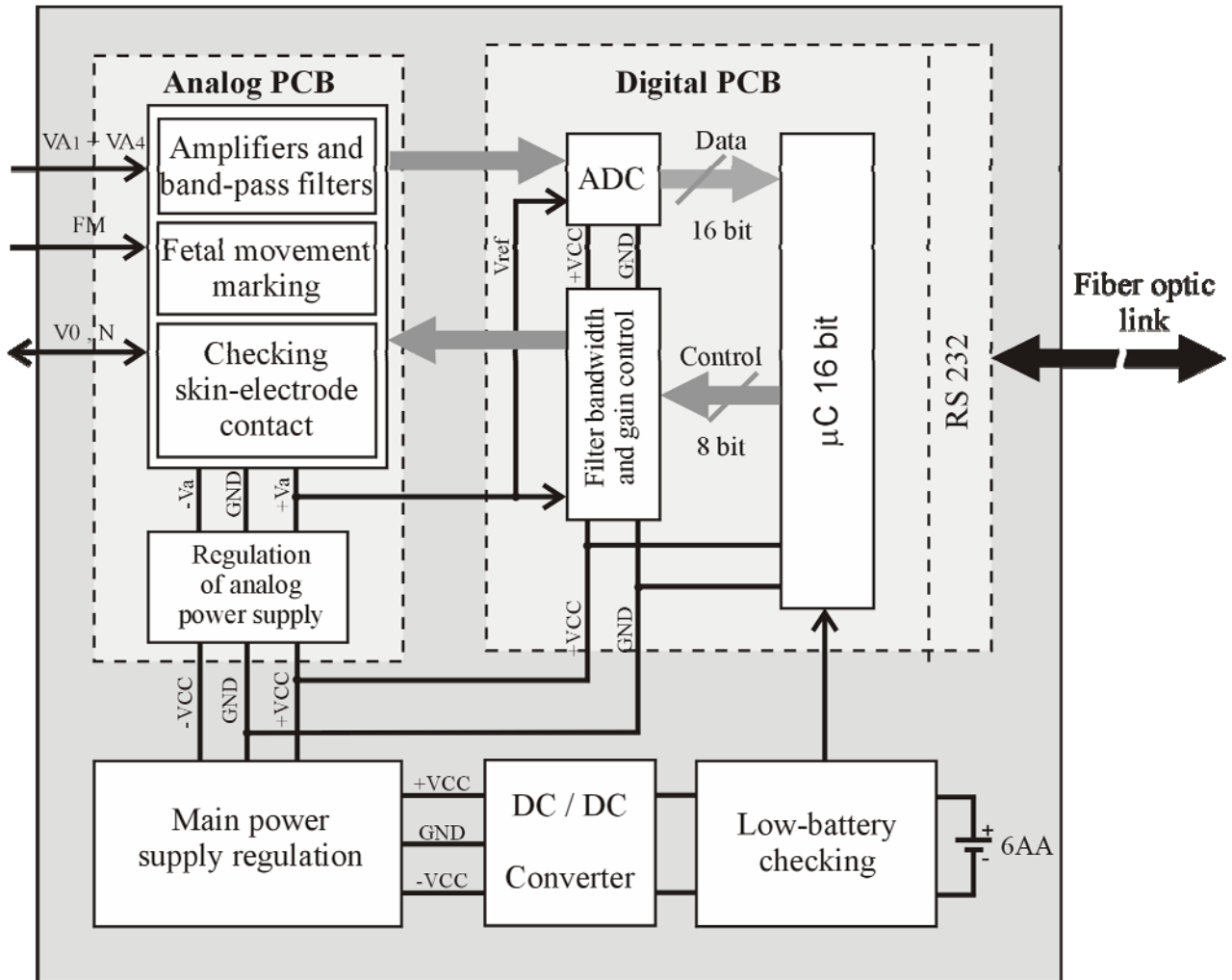


Fig.4. Block diagram of bioelectric signal recorder.

2.2. SIGNAL PROCESSING

The external computer task is to store the incoming data, their on-line analysis and adequate graphical presentation on a monitor screen. The software of the system has been developed basing on LabView (National Instruments) graphical environment for building signal processing applications (Fig.5). The program enables the appropriate control of bioelectric signals recorder. The user has a possibility to establish the optimum amplification for recorded abdominal signals as well as to select the value of lower cut-off frequency of band-pass filters.

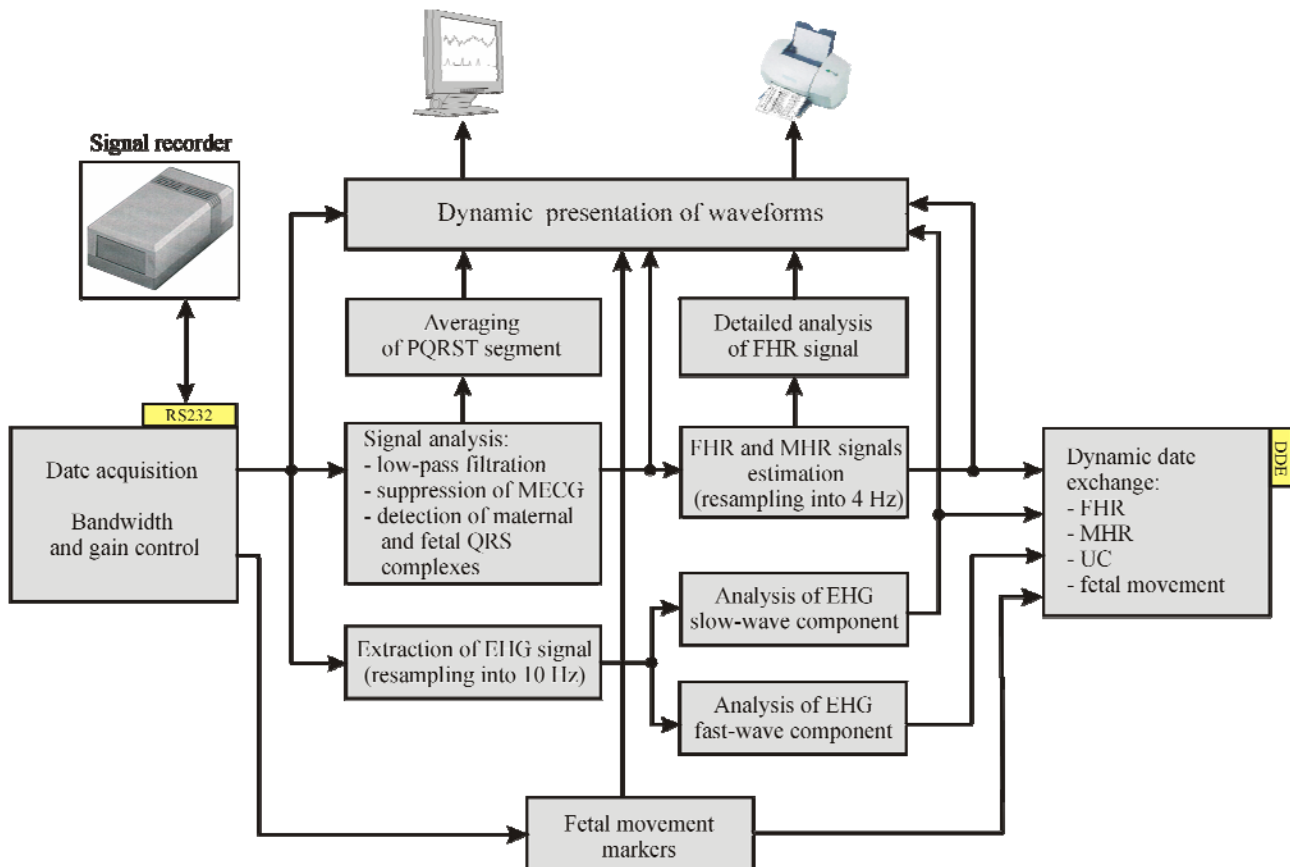


Fig.5. Structure of program for acquisition and analysis of signals recorded from maternal abdomen.

Analysis of abdominal signals comprises the initial filtration of low-frequency and/or mains interferences, suppression of interfering maternal electrocardiogram (additionally, the signal of maternal heart rate is determined), detection of the fetal QRS complexes and thus FHR signal estimation [4], [8], [9]. An example of program panel is shown in the Fig.6. As it can be seen, here is a possibility to observe the dynamically moving signals being recorded on abdomen surface or “pure” FECG signals received after maternal ECG attenuation. Below, there are moving traces of the FHR and maternal heart rate (MHR), the uterine contraction activity (UC) and the marks indicating fetal movements perceived by mother (FM). The software automatically performs the analysis of FHR signals according to procedure presented in Fig.7. In the first step, the FHR signal being represented as the sequence of events is sampled. Assumed sampling period is of 250 ms that eliminates the problem of intervals loss between successive heart beats with a short duration. The original FHR signal is also stored in order to perform the beat-to-beat variability assessment. In succeeding step, the signal loss analysis is carried out as well as averaging and interpolation of FHR values take place. The determined FHR baseline is drawn on a screen in a form of dashed line at the background of FHR trace, whereas accelerations and decelerations events are marked by means of graphical signs illustrating their beginning and duration. Simultaneously, the indices are being determined that describe the instantaneous variability of FHR signal and which are accessible in separate graphical window together with detailed numerical parameters describing accelerations and decelerations.

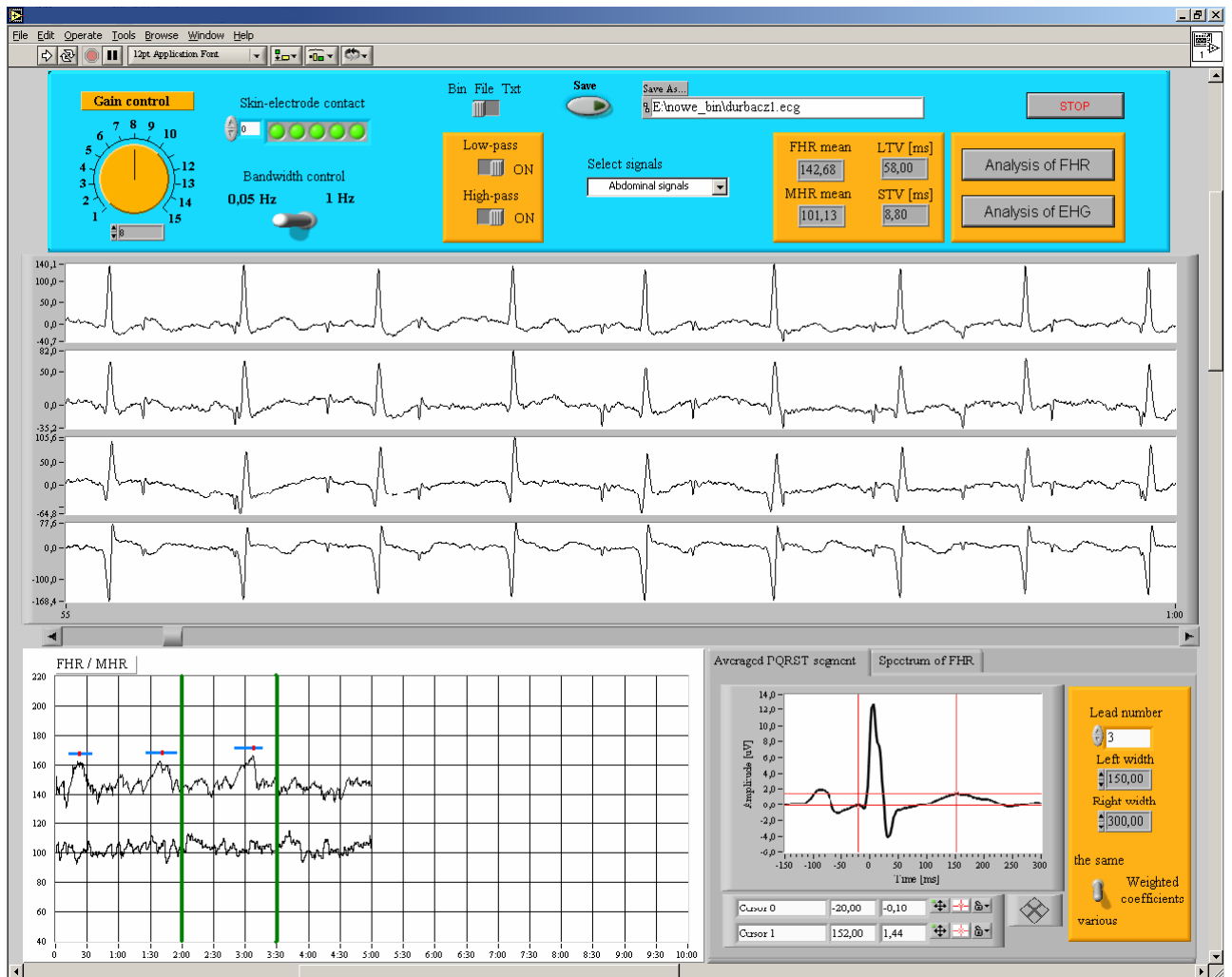


Fig.6. Example of program panel for recording and analysis of abdominal signals.

It is possible to mark a given segment of FHR signal (minimum 1 min) by means of graphic cursor. For this segment, there is a possibility to perform spectral analysis of FHR signal or to compute an averaged fetal PQRST segment from selected abdominal lead. FHR analysis in frequency domain provides very important information on control over fetal heart rhythm, blood pressure changes or control over reactions to respiratory and thermal stimuli by the autonomic nervous system [10]. About 90 % of total signal power is in the band of 0 to 1 Hz. Three basic components can be distinguished in this band. The peak, which corresponds to thermoregulation phenomenon is located below 0.05 Hz. The component, which corresponds to operation of sympathetic and parasympathetic nervous systems is placed in the proximity of 0.1 Hz. The last component, located near 0.7 Hz, corresponds to pseudo-respiratory movements (Fig.8). Analysis of a fetal respiratory activity (presence of this component in the spectrum) is crucial because it allows the differentiation of suspicious cardiocardiographic records into physiological and pathological types.

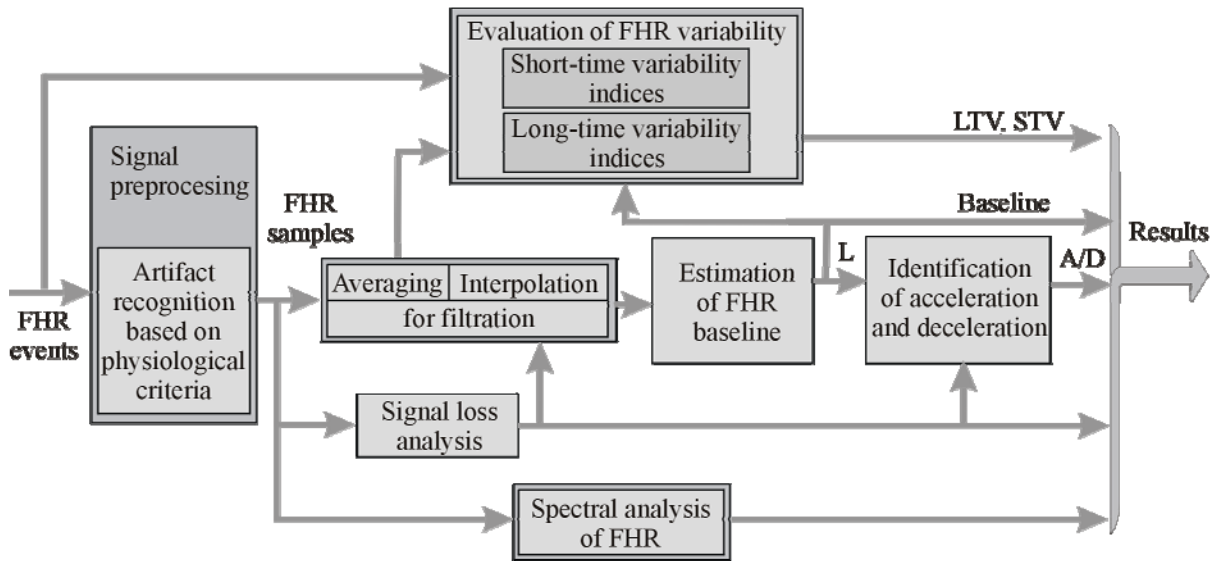


Fig.7. General structure of procedure for automated analysis of fetal heart rate signal.

The studies on evaluation of fetal ECG records and their connection with bad fetal outcome have been mainly focused on the analysis of ST segment morphology changes and the relation of T-wave amplitude to QRS amplitude as well as focused on the measurement of PR distance relation to fetal heart rate [4]. FECG signal recorded on maternal abdomen surface only in some cases allows direct observation of QRS complexes that have relatively high amplitude. The P and T waves having considerable smaller amplitude are invisible. In such case, method of improvement of low signal-to-noise ratio (SNR), which is commonly used in systems analysing biomedical signals, appears to be very helpful. In non-invasive fetal electrocardiography, this technique enables the exposing of FECG signal morphology and then carrying out the quantitative evaluation of amplitude-time relationships among determined waves. The user can select an FECG lead number, determine a width of averaged PQRST segment (the left and right width being calculated from the moment of R wave appearance) and to establish a way of averaging (using the same or various weighted coefficients). On averaged PQRST segment, with aid of graphic cursors one can effect the relevant measurements of the amplitude of given waves expressed in μV , and their duration expressed in msec (Fig.9).

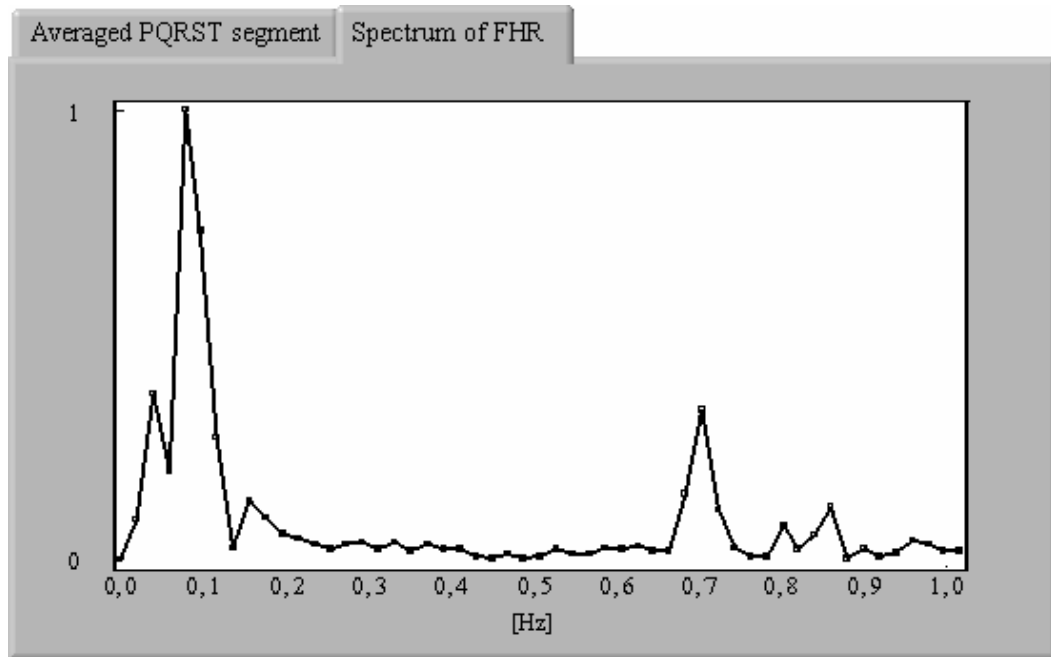


Fig.8. Spectrum of fetal heart rate signal – detection of component of pseudo-respiratory fetal movements.

From the abdominal signals, as a result of low-pass filtration (cut-off filter frequency 5 Hz), a signal characterizing the electrical activity of uterine muscle – EHG is separated. This signal undergoes the resampling operation (sampling frequency equal to 10 Hz), and two characteristic components are determined: slow wave – contraction component (UC) and fast wave – action potentials component [3].

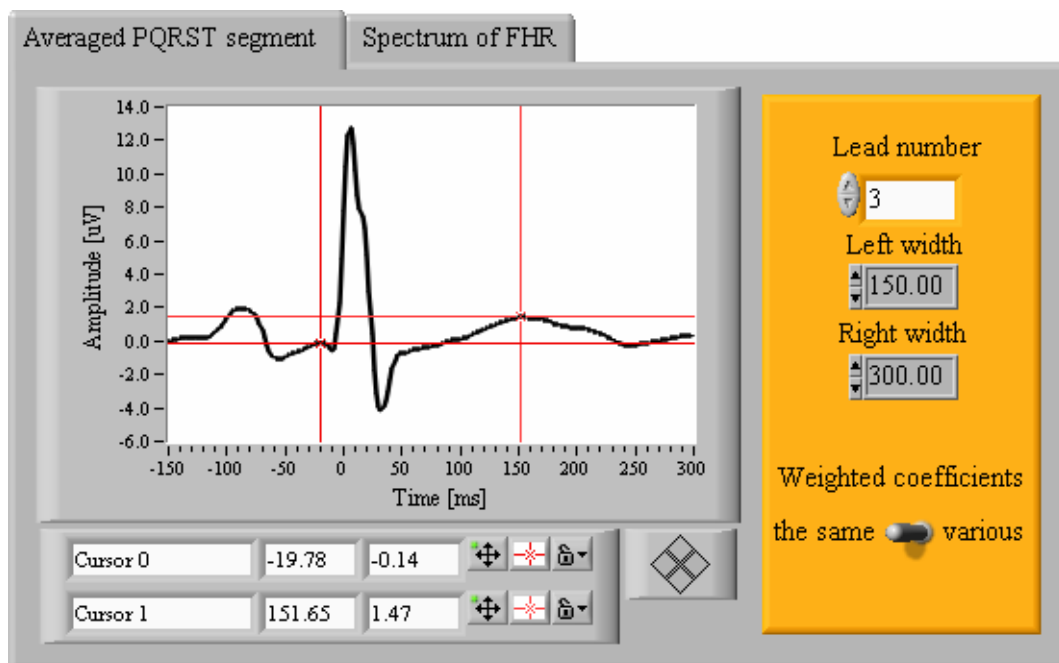


Fig.9. Averaged PQRST segment of fetal electrocardiogram signal in a selected lead – averaging by weight has been selected, which means that the last few PQRST complexes have assigned the largest weights.

Analysis of slow-wave component is a classical analysis of contraction trace in time domain that delivers timing parameters: start time, duration, amplitude and area of contraction. Fast-wave component analysis makes possible the determination of spectral contraction parameters. Utilising the information on timing EHG parameters, the segments that include bursts of action potentials, which correspond to particular contractions, are isolated. The segments undergo the frequency analysis that enables determination of spectral parameters of contraction: intensity, power, median frequency and the frequency at maximum power. All the parameters are possible to be displayed in separate graphic window on demand of the system user. The program allows the user to select forms of the graphic presentation of recorder signals. Furthermore, it is possible to choose the set of parameters of automated analysis and to establish the rules and threshold determining the occurrence of alarming situations. All the signals, together with analysis results are stored in the system archive where a possibility of their later review is ensured.

The instrumentation presented in this paper can also be incorporated into multistation system for monitoring of health condition of mother in labour and her unborn baby – MONAKO. At that time, the application created in LabView environment together with the recorder of bioelectric signals constitutes a virtual fetal monitor. The data from this virtual fetal monitor are transferred by means of DDE communication to another application working in parallel that controls the MONAKO system. Of course, in any moment there is a possibility of LabView-operated program recalling and performing e.g. a morphology assessment of FECG signal or spectral analysis of FHR signal.

3. CONCLUSIONS

Developed system for the diagnostics of a fetal condition, based on bioelectric signals recorded from the surface of maternal abdomen, initiates a new technique in fetal monitoring field. During its realization, a few novel methods of signal processing have been accomplished. The most important ones are as follows: suppression of maternal electrocardiogram dominating in abdominal signals received, precise detection of fetal QRS complexes, extraction and analysis of EHG signal, filtration-statistical algorithm of baseline estimation with analysis of FHR signal loss episodes and finally removing of artefacts within accelerations and decelerations. The methods specified have enabled the considerable improvement of signal processing in relation to previously used methods.

During the work, the universal low-noise recorder of bioelectric signals has been designed. Together with a standard personal computer and suitable software, it permits the replacement of classical ultrasound-based fetal monitor. Owing to both the new algorithms for analysis of classical FHR and UC as well as the new parameters obtained from FECG morphology assessment and spectral analysis of FHR and EHG signals the high diagnostic quality for fetal distress estimations has been reached.

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