fetal monitoring, cardiac cycle timing,
fetal electrocardiography, fetal heart rate.

Adam MATONIA*, Janusz JEŻEWSKI*, Tomasz KUPKA*,
Krzysztof HOROBA*, Janusz WRÓBEL*, Michał WIDERA*

COMBINED ANALYSIS OF FETAL ELECTROCARDIOGRAM AND SYSTOLIC TIME INTERVALS

Cardiotocography as a simultaneous recording of fetal heart rate (FHR) and uterine contraction activity is a basic method of evaluation of fetal condition. Correct variability of the fetal heart rate is an indirect sign of adequate oxygenation of a fetus. Unfortunately, the reverse case is not always true, signs suggesting pathological changes can also appear in recording when the fetal is not at risk. The cardiotocography shall then be recognized as a more screening than diagnostic method. It will be interesting to develop a non-invasive method being complementary to routine cardiotocography. This method should allow the adequate prediction of a bad neonatal outcome when the test is abnormal. The paper shows the system that makes possible cardiotocograms analysis in parallel with the assessment of additional parameters determined from comparison of mechanical and electrical fetal heart activity signals. The studies are aimed at development of set of parameters that are high correlated with clinical outcome.

1. INTRODUCTION

Diagnostics of unborn baby is mainly aimed at prediction and detection of occurrence of intrauterine hypoxia. Consequences resulting from fetal hypoxia appear in its heart activity. In today perinatal medicine, there is commonly used the non-invasive cardiotocographic examination that makes possible the simultaneous observation of Fetal Heart Rate (FHR) at the background of fetal movement and uterine contraction activity [2]. The FHR signal is determined on a basis of duration of intervals between consecutive cardiac cycles. Among many various techniques of interval determination, presently the most popular is ultrasound method which records mechanical activity of fetal heart. Determination of FHR signals relies on detection of cardiac systoles and diastoles using the analysis of Doppler shift of ultrasound beam reflected from moving valves (walls) of fetal heart (Fig. 1). The FHR signal can be determined on the basis of electrical activity of fetal heart – fetal electrocardiogram (FECG). It allows the much more accurate location of particular heart beats – R waves [1]. In electrocardiogram acquisition, two methods are distinguished: direct method where an electrode is attached to fetal body surface and indirect method where the measurement electrodes are located on the surface of mother body. The first method provides a good quality signal but is invasive and can be used only during labour. The

* Institute of Medical Technology and Equipment, 118 Roosevelt St, 41-800 Zabrze, POLAND
tel./fax: (32) 2716013/2712312, e-mail: adamm@itam.zabrze.pl

indirect method is completely non-invasive and can be used from 12th week of pregnancy but recorded FHR signals are interfered by mother's electrocardiogram and muscular artefacts (Fig.1).

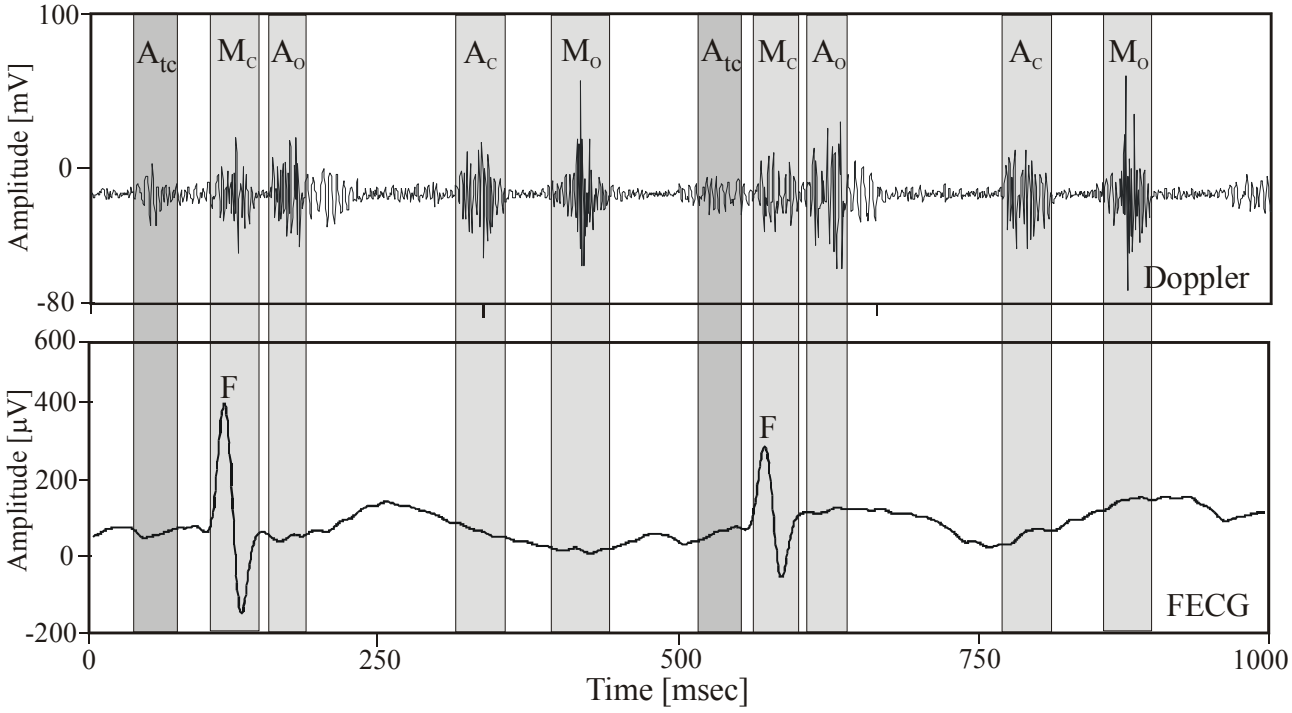


Fig.1. Signal of mechanical and electrical activity of fetal heart recorded simultaneously. M_C and M_O – atrioventricular valve closure and opening, A_C and A_O – semilunar valve closure and opening, A_{tc} – atrial activity, F – fetal QRS complexes.

Correct variability of fetal heart rate is an indirect proof of proper oxygen supply of fetus. However, suspicious features of FHR record can also appear when there is no fetal distress. Undoubtedly positive and encouraging for wide application feature of cardiotocographic monitoring (CTG) is its high specificity reaching 96-98% and negative prognostic value verified by good condition of neonates. Still, its low, included within 21-31% sensitivity and positive prognostic value is worrying because in too many cases it raises the obstetricians' excessive operational activity unjustified by fetal state. Therefore, the cardiotocography is considered rather screening than diagnostic method. It is believed that after recognition of disturbances in heart rate record it is necessary to verify the real fetal condition. Development of universal diagnostic method characterized by possibly highest predictive value with reference to intrauterine fetal state is important and still unsolved problem of present-day perinatology. This knowledge is substantial for early identification of fetus distress and for determination of optimal delivery term.

We have developed a new approach to fetal monitoring system which enables the standard cardiotocogram analysis and provides new parameters. These parameters are determined on the basis of detailed analysis of electrical and mechanical heart activity together with their mutual relations. Innovation of our approach relies on a way of recording of electrical activity of fetal heart. We used indirect recording of fetal ECG signal, which enables application of the system during both pregnancy and labour. Performed tests are aimed at gaining optimal set of parameters and indices enabling verification of doubtful CTG records. Collection of representative records and their analysis results will allow to evaluate retrospectively given parameters with reference to the real

neonatal state. For parameters reaching the highest prognostic value there is planned the quantitative estimation of their value changes and establishing of reference ranges for second and third pregnancy trimester. Fig. 2 shows the way of determination of parameters resulting from mechanical and electrical heart activity correlation. According to [5], [7] the most useful parameter for assessment of fetal myocardium is so called pre-ejection period. It is defined as a time counted from the beginning of fetal QRS complex appearance (Q-wave appearance) to the moment of aortic valve opening. In the system there are also determined other parameters: isovolumetric conduction time (IVC) or left ventricular time (LVET).

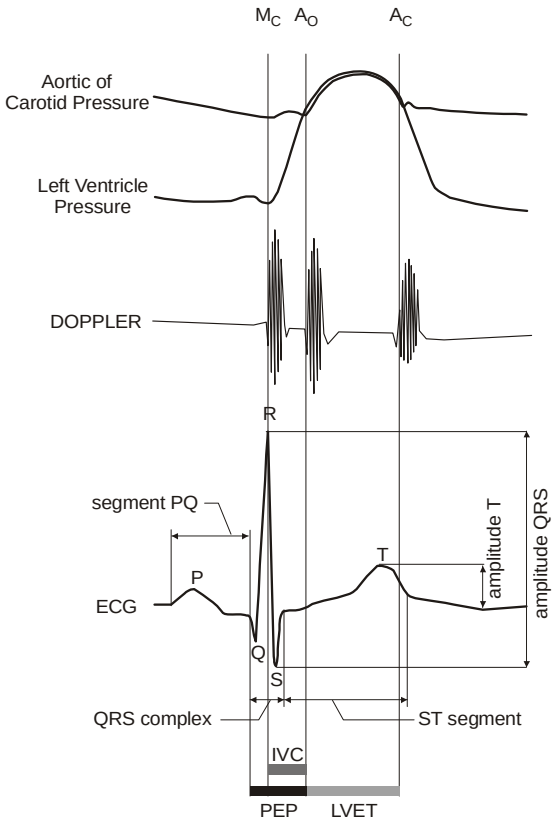


Fig.2. The measurement of parameters being the result of mechanical and electrical fetal heart activity correlation as well as coefficients describing the changes of morphology of FECG signal: PEP – pre-ejection period, IVC – isovolumetric conduction time, LVET – left ventricular time.

Of course, having electrical heart activity signal, morphology of fetal ECG record can be evaluated, i.e. measurement of amplitude and time relations between particular waves. It is predicted that studies on evaluation of FECG records morphology and their connection with fetal distress will be focused mostly on analysis of ST segment changes, determination of relationship between T-wave amplitude and QRS complex [6] as well as correlation of PR segment with FHR signal value [3].

2. INSTRUMENTATION

Diagnostic set has been constructed on the basis of computer cooperating with data acquisition card DAQCard-A1-16XE-50 (National Instruments). Integral part of the set (Fig. 3) is the fetal monitor MT-430 (Toitu) having two independent ultrasound channels as well as the channel for monitoring of uterine contraction activity. The second ultrasound channel is used, by definition, for monitoring of twins. However, in our system it is used for monitoring of single pregnancy where, regarding different measurement conditions (different location of ultrasound transducer), it allows in some cases obtaining better quality of ultrasound signal. Ultrasound signals (US_1 and US_2) together with actograms (FM_1 and FM_2), uterine contractions signal and determined by a fetal monitor the fetal heart rates (FHR_1 and FHR_2) are accessible on analog output of fetal monitor and next are sent to data acquisition card.

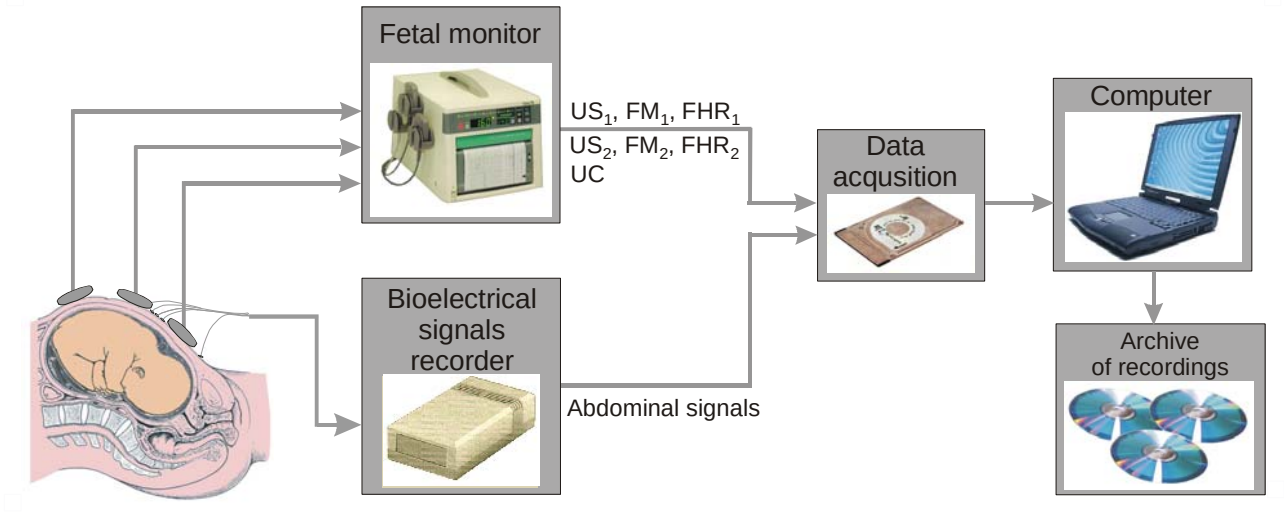


Fig.3. Proposed diagnostic system enabling the simultaneous acquisition and analysis of electrical and mechanical activity of fetal heart – electrocardiogram and systolic time intervals.

Signals of electrical fetal heart activity is recorded in the system by means of separate bioelectrical signals recorder circuit [4]. Non-invasive measurement of fetal ECG signal from abdominal walls can be perform during either pregnancy or labour. The recorder enables the measurement of four abdominal signals representing electrical activity of a fetal heart. The measurement of as many as four signals is caused by the fact that frequently during indirect recording of FECG signal the useful component is visible only in one of the leads. Such a solution is a certain compromise between the number of used electrodes and the possibility of recording a good quality FECG signal. The basic merits of the presented recording module are very low level of its own noise which does not exceed 0.5 μV (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). 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 circuit for checking a skin-electrode connection and the low battery check circuit. This information and the gain regulation are sent via the digital inputs of DAQ card to the computer where they are displayed on a monitor screen in the form of graphical marks. Abdominal signals are sent to analog inputs of acquisition card that converts all the signals into digital form with the frequency of 2 kHz. Such the sampling frequency results from Doppler signals band reaching the 1 kHz. In case of abdominal signals, this frequency ensures precise R waves detection and thereby accuracy of T_{RR} intervals determination from FECG signal at the level of 0.5 ms. Such a high sampling frequency is not required for the rest of signals. Therefore, they are completely sampled and than displayed and archived. It is done by the program developed in LabView (National Instruments) graphical environment for building signal processing applications.

Necessity of using separate measurement circuits for recording of electrical and mechanical fetal heart activities causes producing of additional shift between these signals that does not result from monitored phenomena. It is because always electrical heart activity (FECG waveform) gets ahead of and considerably influences mechanical activity. The shift in question is a result of introduced by electronic circuits the differentiated delay in signal conversion channels: ultrasound and electrocardiotocographic. The action of fetal heart valve was modeled by membrane of a loudspeaker controlled by the rectangular signal from generator. Uneven filling of rectangular signal (1/10) causes the impulse movement of membrane similar to the one that occurs during opening and closing of fetal heart valve. The loudspeaker has been put in water, where water column height was equal to the distance between fetal heart and abdominal wall. At water surface there was an ultrasound head placed on latex support. In this way, the measurement conditions were reached, similar to the real conditions in which the Doppler signal characterizing mechanical fetal heart activity is obtained. Simultaneously, the generator signal reflecting the electrical heart excitation signal was sent to the input circuit of bioelectric signal recorder. Displaying of signals on monitor screen enabled precise measurement of the ultrasound signal delay in relation to electrical signal and thereby correct determination of parameters resulting from correlation between mechanical and electrical fetal heart activities.

3. RESULTS

The records have been collected in Department of Obstetrics and Gynaecology of Medical University School of Silesia. All patients were familiarized with the scope of conducted tests and gave their informed consent for it. The database contains 25 multi-channel records taken between 24 and 42 week of pregnancy. Apart from the records the database contains analysis outcomes, data

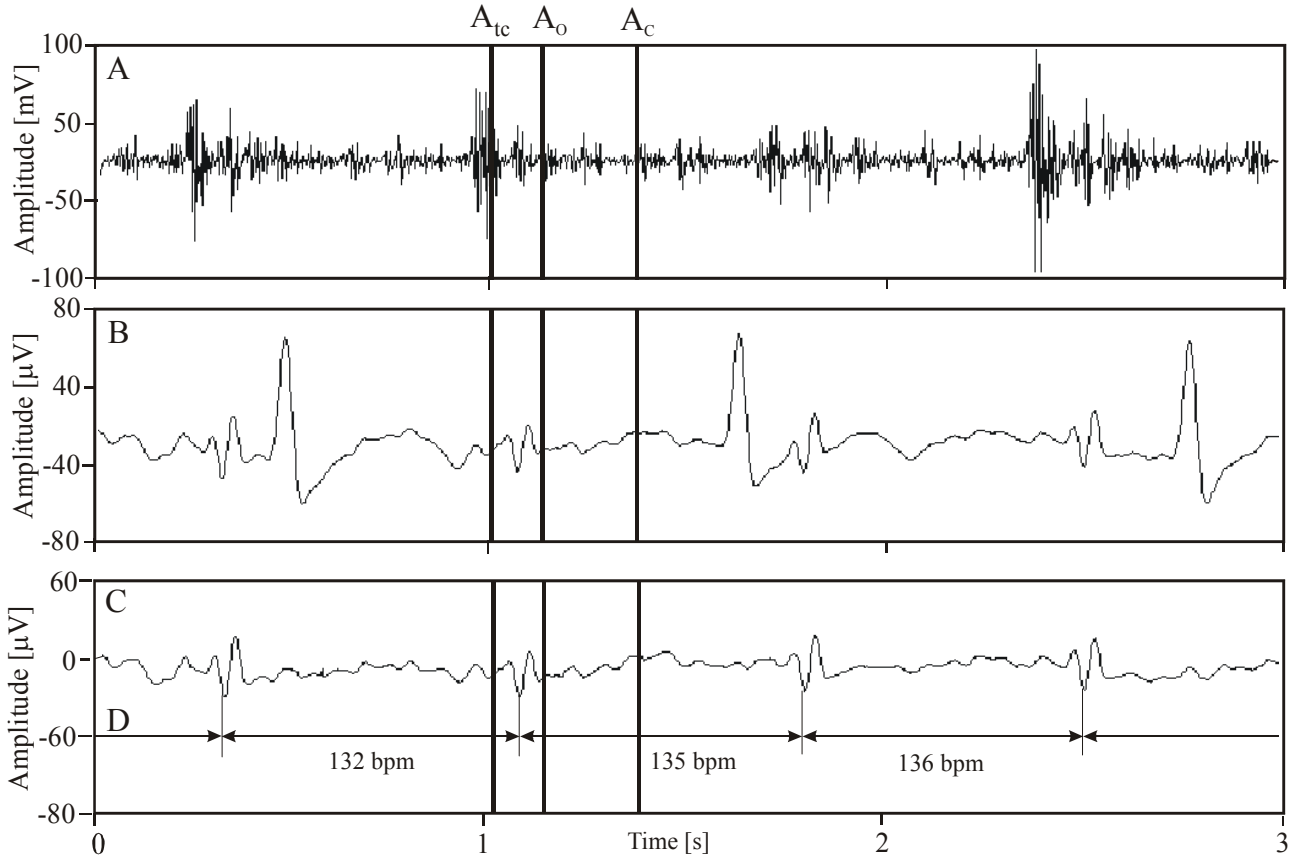
concerning general state of pregnant women, pregnancy course as well as results of additional biochemical and biophysical tests performed after labour and the data received from pregnancy chart.

During recording of all signal mentioned before, particular attention was paid to obtain their best possible quality. The most important was proper location of ultrasound transducers as well as proper preparation of skin (removal of horny layer of epidermis) for placing FECG signal recording electrodes. Next, in off-line mode, signal analysis and determination of additional parameters are performed with the use of a relevant computer program.

First, on the basis of visual analysis of recorded signals, person controlling the monitoring chooses the channel with the best quality of ultrasound signal (Fig. 4A) and abdominal signal (Fig. 4B). Abdominal signal undergoes preliminary digital filtration aimed at suppression of slow wave and muscular interferences. In the sequel, there is performed the procedure of dominating maternal electrocardiogram suppression thanks to which "pure" FECG signal is obtained (Fig. 4C).

The next step is automatic detection of R waves, determination of consecutive T_{RR} intervals and calculation on their basis of the instantaneous values of FHR signal (Fig. 4D). Computer program enables, by means of a scroll bar, to choose indicated fragments of signals and to display them in a scale of 10, 5 or 2,5 cm/s. Graphical cursors: A_{tc}, A_O and A_C allow marking of given events and thus calculation of PEP, IVC and LVET parameters.

The values of parameters together with indicators characterizing the change of FECG signal morphology are displayed in a proper table below the diagram (Fig. 4E). Unfortunately, indirect recording of FECG signal enables only analysis of QRS complex that has relatively large amplitude. P and T waves with considerably smaller amplitude are usually invisible. Therefore, the measurement of characteristic time-amplitude relations is performed on averaged segment of PQRST that can be displayed in the separate graphical window. The PQRST segment is calculated by averaging of last 50 fetal cardiac cycles counted from position of Q cursor in relation to which the current PEP parameter measurement is made. Below the main diagram and table with results there is an auxiliary diagram of FHR and FM traces received from cardiotocograph (Fig. 4F). The traces are plotted in a standard 1 cm/min scale. The program analyses these signals in order to determine the baseline, detect acceleration and deceleration (their beginning and duration is graphically marked). Additionally, by means of "arrows" on the diagram, the site of currently performed analysis is being marked and correlation parameters are being determined. It enables a physician to interpret properly the value of calculated parameters and indicators in relation to the events occurring in FHR signal. The program allows us to record the outcomes of performed analysis of signals and calculated parameters. There is a possibility of their later review and supplement. Whereas after a labour, the verification of diagnostic and prognostic value of a given parameter is done in relation to fetal outcome of a newborn. In the form of retrospective analysis, the evaluation of fetal outcome has been defined on the basis of: percentile of birth mass for the population, Apgar scores in 5-th minute of life, results of umbilical vain blood gasometry, data on newborn stay in intensive care unit or on caesarean section performed due to the risk of intrauterine fetal asphyxia [8].



E

PEP [ms]	IVC [ms]	LVET [ms]	T/QRS	PR [ms]	T_{RR} [ms]	FHR [bpm]
65	44	141	0,19	105	454	132

F

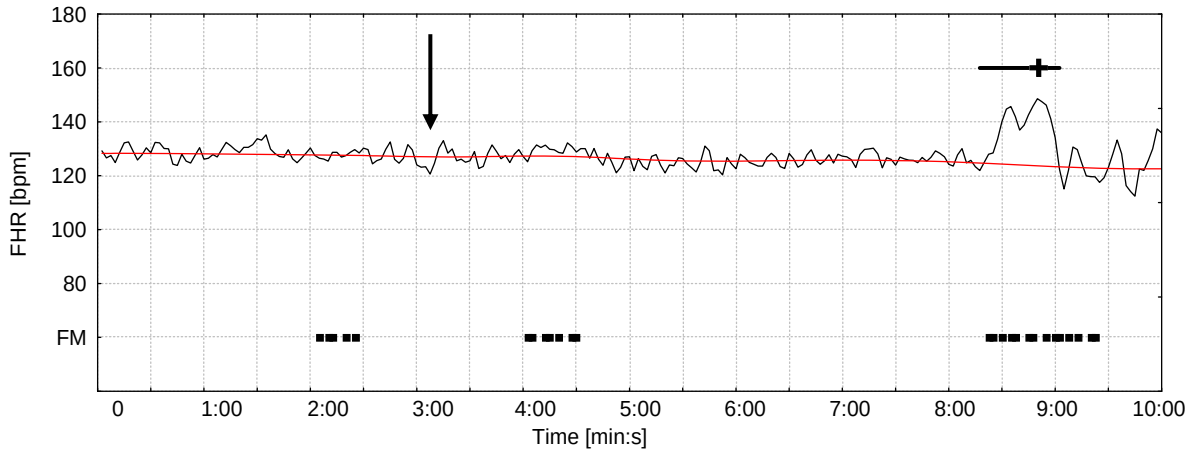


Fig.4. The example of analysis of signals describing the mechanical and electrical activity of fetal heart on the background of simultaneously presented cardiotocographic trace.

4. CONCLUSIONS

Biophysical methods which enable the objective assessment of the fetal hypoxia during pregnancy and labour, play the substantial role in today perinatal medicine. Biophysical diagnostics is mainly based on the analysis of fetal heart activity, as the blood circulation constitutes an essential mechanism of homeostasis ensuring appropriate internal environment for the fetus. Nowadays, regarding the non-invasiveness, the cardiotocographic monitoring is commonly used. The analysis of FHR record features makes possible to assess only indirectly the state of hypoxia. Unfortunately, it is very frequent situation that characteristic FHR record features suggesting the hypoxia appear both in case of fetal distress and its missing. Such a not unanimous risk assessment is particularly dangerous during the labour, when it is not possible to repeat the record for verification of the results obtained. The complementary methods are in request that could allow to verify the suspected CTG records and thereby appropriately and rapidly to recognize the situation endangering the baby during labour. The designed set for fetal diagnosis support, apart from standard FHR signal analysis, allows the user to determine additional parameters being an assessment result of correlation of the electrical and mechanical fetal heart activities. The database of the representative records will enable in the future the selection and establishing of numerical criteria for parameters evaluation which will have the best correlation to fetal outcome.

BIBLIOGRAPHY

[1] JEŻEWSKI J., HOROBA K., WRÓBEL J., SIKORA J., GACEK A., MATONIA A., KUPKA T., Monitoring of mechanical and electrical activity of fetal heart: Determination of the FHR. Arch. Perinat. Med., Vol. 8, pp. 33-39, Poznań, 2002.

[2] JEŻEWSKI J., WRÓBEL J., Kardiotokografia Komputerowa. In: Biofizyczna diagnostyka płodu i noworodka, red. G.H. Bręborowicz, J. Gadzinowski, OWN, pp. 54-80, Poznań, 1998.

[3] MALEWSKI Z., Elektrokardiografia płodu. In: Biofizyczna diagnostyka płodu i noworodka, OWN, pp. 157-162, Poznań, 1998.

[4] MATONIA A., JEŻEWSKI J., WRÓBEL J., KUPKA T., HOROBA K., Optymalny tor wejściowy do nieinwazyjnej rejestracji sygnału EKG płodu, XII Konferencja Naukowa Biocybernetyka i Inżynieria Biomedyczna,
pp. 182-186, Warszawa, November 2001.

[5] MURATA Y., MARTIN C. B., IKENOUE T., LU P. S., Antepartum evaluation of pre-ejection period of the fetal cardiac cycle, AM. J. Obstet. Gynecol., Vol. 132, pp. 278-283, January 1978.

[6] ROSEN K. G., LUZIETTI R., Intrapartum fetal monitoring: its basis and current developments, Prenat. Neonat. Med., Vol. 5, pp. 155-168, June 2000.

[7] SAMPSON M. B., Antepartum Measurement of the Preejection Period in High-Risk Pregnancy, Obstet. Gynecol., Vol. 56, pp. 286-295, September 1980.

[8] SIKORA J., Cyfrowa analiza kardiotokogramu w klinicznej prognozie stanu płodu, Klin. Perinat. Ginek., OWN, Suppl. 21, Poznań, 2001.

This study was supported by the State Committee for Scientific Research, Warsaw, Poland (KBN Grant No. 4 T11E 006 22).