EVALUATION OF THE QRS DETECTION ALGORITHMS IN RELATION TO FETAL HEART RATE ESTIMATION

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Abstract: **Fetal electrocardiography has become the object of many research investigations carried out in recent years. Two methods of fetal electrocardiogram (FECG) acquisition can be distinguished: direct and indirect. The direct method is invasive, whereas the indirect one is a fully non-invasive approach and allows signal recording during labour and pregnancy. Unfortunately, the FECG recorded from the maternal abdomen, due to very low amplitude is sensitive to noise. There can occur both the noise signals typical for adult electrocardiography as well as the very specific noise signals (maternal electrocardiogram and uterine contraction activity). These interferences are the serious problem for computerized analysis of FECG, which comprises the initial filtration, suppression of maternal electrocardiogram and detection of the fetal QRS complexes. Correct detection is very crucial for estimation of the fetal heart rate and analysis of morphology changes in FECG signal. Unfortunately, low level of the useful signal, a wide range and specific characteristics of the noise signals and most of all a lack of freely distributed database of the reference signals make the evaluation of the QRS detection efficiency very difficult. In this work different fetal QRS detection algorithms were evaluated basing on the software generator of synthesized FECG signals.**

Introduction

Fetal electrocardiography as the technique opening the new possibilities for perinatal diagnostics has become the object of many research investigations carried out in recent years. This technique, like the commonly used ultrasound technique, enables determination of the fetal heart rate (FHR) signal however with much higher accuracy. Much more important is that the measurement of electrical activity of fetal heart enables to carry out assessment of the morphology of the fetal electrocardiogram – FECG and consequently early detection of the fetal hypoxia.

Two methods of fetal electrocardiogram (FECG) acquisition can be distinguished: direct and indirect. The direct method is invasive and it can be applied during labour only, whereas the indirect one is a fully non-invasive approach and allows FECG recording also during pregnancy (since 16th week). Unfortunately, the signal recorded from the maternal abdomen, due to very low amplitude (several μV) is very sensitive to noise. There can occur both the noise signals typical for adult electrocardiography [3]: low frequency, powerline and muscle interference as well as the very specific noise signals which can be met only during recording of FECG from maternal abdomen:

- maternal electrocardiogram (MECG) of the wide range of common frequencies and amplitude exceeding the FECG signal many times
- electrohysterogram (EHG), abrupt interferences of a high energy which originate from the uterine activity during labour.

These specific interferences are the serious problem for computerized analysis of FECG. In the work [11] a comprehensive comparison has been carried out concerning the efficiency of several different maternal ECG suppression methods basing on: weighted summation of abdominal signals [1], spatial filtration [2,9] as well as subtraction of "reference" MECG signal. Obtained results confirmed a good efficiency of the methods investigated, however the method based on subtraction of reference P-QRS-T fragment was found as the best one [10]. This method enables the strongest suppression of maternal ECG and at the same time the lowest distortion of the FECG component.

After suppression of maternal component the detection of fetal QRS complexes is carried out. It is very crucial for estimation of the fetal heart rate and analysis of morphology changes in FECG signal. Unfortunately, low level of the useful signal, a wide range and specific characteristics of the noise signals and most of all a lack of freely distributed database of the reference signals make the evaluation of the QRS detection efficiency very difficult. In this work different fetal QRS detection algorithms were evaluated basing on the software generator of synthesized FECG signals.

Materials and Methods

Electrocardiogram is a record of the changes of action potentials of heart muscle which occur during the consecutive cardiac cycles. Fetal electrocardiogram just like adult ECG consists of waves marked consecutively: P, Q, R, S, T which appear quasi-periodically (Fig. 1).

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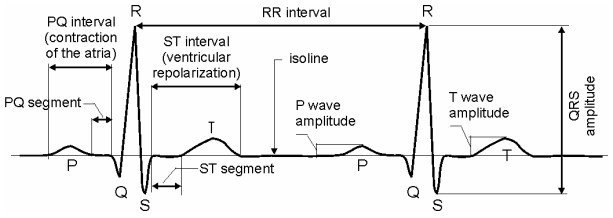

Figure 1: The structure of the fetal electrocardiographic trace

Detection of QRS complexes in the FECG signal leads to determination of their fiducial points (FP_i) corresponding to R waves (Fig. 2).

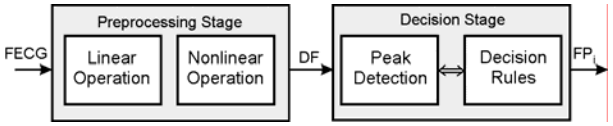

Figure 2: Structure of the fetal QRS detectors

This is accomplished by means of the detection function (DF), whose aim is to process the FECG signal to the form enabling application of the decision rules and then localization of the correct QRS complexes [5]. The DF is expected to generate only one positive peak for every R wave. This function should not generate such peaks for any other waves of electrocardiogram and for possible noise signals. The detection function is fed to the decision block, which task is to detect the peaks of DF and then, on a basis of certain decision rules, to judge if the QRS occur or not in FECG. This leads to determination of fiducial points.

As it can be noticed in Fig. 2 the linear and nonlinear operations are applied to the FECG signal in order to determine the DF. Three different linear operations have been used in the work:

- LO1 – linear filtration is accomplished by the cascade of several digital filters of the amplitude-frequency characteristics matched to the frequency spectrum of the fetal QRS complex [3] (middle frequency of 27 Hz and bandwidth of 24 Hz).
- LO2 – linear combination of the first and the second derivative [3,5] of the FECG (the weight coefficients have been set empirically at $w_1 = 1$ and $w_2 = 2$). Before the derivatives are determined the FECG is preliminary filtered using a low-pass Bessel filter of the second order and cut-off frequency of 60 Hz.
- LO3 – linear filtration accomplished by the cascade of the second-order high-pass Butterworth filter (cut-off frequency of 25 Hz) and the fifth-order low-pass Butterworth filter (cut-off frequency of 60 Hz).

The signal after linear operation requires rectification by nonlinear filtration. According to the work [6] four nonlinear operations have been applied:

$$\text{NO1:}\quad DF(n)^* = \left|x_1(n)\right| \tag{1}$$

$$\text{NO2:}\quad DF(n)^* = \left[x_1(n)\right]^2 \tag{2}$$

$$\text{NO3:}\quad x_2(n) = \frac{1}{2K}\sum_{k=0}^{2K-1}\left|x_1(n-k)\right| \tag{3}$$

$$DF(n) = \frac{1}{2K}\sum_{k=0}^{2K-1} x_2(n-k) \tag{4}$$

$$\text{NO4:}\quad x_2(n) = \frac{1}{2K}\sum_{k=0}^{2K-1}\left[x_1(n-k)\right]^2 \tag{5}$$

$$DF(n) = \frac{1}{2K}\sum_{k=0}^{2K-1} x_2(n-k) \tag{6}$$

**When the NO1 and NO2 nonlinear operations were applied the obtained detection function required additional smoothing with the help of the moving average filtration in 30-ms window in order to obtain a single peak in each localization of the fetal QRS complex.*

The detection functions obtained in the ways mentioned above were analyzed in order to detect all peaks corresponding to fetal QRS complexes. In the first stage detection of a given DF peaks was carried out by the use of the basic decision block marked as DS1 (Decision Stage). It decides whether the DF peaks is correct or not basing on comparison of DF amplitude with the established and continuously adjusted detection threshold (THR). The QRS complex is preliminary localized in the place of the first crossing of the detection threshold and DF (on the rising slope of DF peak). After that, the place of the second crossing of THR and DF is found (on the falling slope of DF peak). Precise localization of fetal QRS complex e.g. determination of their fiducial point (FP) is performed by determination of the maximum of detection function between previously found crossing points:

$$FP(i) = \max_{p_1(i)<n<p_2(i)} DF(n) \tag{7}$$

where:
$p_1(i)$ – the crossing point of the THD and the rising slope of DF peak for the i-th QRS complex
$p_2(i)$ – the crossing point of the THD and the falling slope of DF peak for the i-th QRS complex.

The amplitude of detected DF peak is used to predict an amplitude of the next peak e.g. to adjust the detection threshold. Mostly, in the iterational evaluation of the detection threshold the amplitude of the next peak is predicted according to the following formula:

$$\hat{DF}(i+1) = A * \hat{DF}(i) + (1-A) * DF(i) \tag{8}$$

where:

$\hat{DF}(i)$ – predictive value of DF peak corresponding to the i-th fetal QRS complex,
DF(i) – the value of DF peak corresponding to the i-th fetal QRS complex,
A – constant value established empirically at 0.85

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Then, the detection threshold is calculated as a certain percentage of the predictive amplitude of DF peak:

$$THR(i) = C_{\%} * \hat{DF}(i) \quad (9)$$

where: $C_{\%}$ - the percentage coefficient defining the detection level, determined empirically and equal to 0.45.

In the first stage a very simple decision rule was applied in the DS1. The detector was put to inactive state for certain time period (200 ms) after a valid QRS complex was localized. In the successive stages of the analysis following decision rules were added:

DS1A – the detection threshold is decreased by the value of 25% of actual THR and repeat searching is carried out when peak is not found in expected localization, this operation is repeated three times. The range of 1.75 of actual RR(i) was set, where RR(i) = FP(i) – FP (i - 1) and defines the interval between consecutive heart beats.

DS1B – the physiological-based rule defining in what range and how the interval between consecutive heart beats can change [4]. This rule is based on the two physiological properties of the fetal heart activity:

- the value of the acceptable difference between two consecutive RR intervals is in direct proportion to the intervals duration
- the larger difference are accepted during deceleration (when the consecutive intervals become longer) than during acceleration (the consecutive intervals shorten).

According to the above criteria only these RR(i) intervals are accepted which fulfil a following condition:

$$\underset{RR_{MIN}}{RR_{i-1}^{ms} - 0.43 * \Delta_{i-1}} < RR_i^{ms} < \underset{RR_{MAX}}{RR_{i-1}^{ms} + \Delta_{i-1}} \quad (10)$$

Despite the basic decision stage a brand new stage marked as DS2 was developed and applied. Its functioning is based on the recognition of the detection function peaks by so called "level detection technique". It is based on searching all peaks on the established levels (ten constant levels have been applied). The output of the DF peaks detection block is the array of possible peaks, where number of rows defines the number of detection levels and number of columns relates to the number of FP found on a given level. Valid FP was recognized by means of the composite decision rule which has been proposed in [7]. This rule takes into account not only a change of consecutive RR intervals but also acceptable changes of the amplitude and shape of FECG signal in the fragment defined by a given FP. When all these conditions are fulfilled the recognized FP can be marked as corresponding to true QRS complex, but always the FP found on the highest level is selected.

Evaluation of implemented QRS detection algorithms was carried out by using previously developed software generator of synthesized FECG signals. The signal modelling was carried out with a help of Hermit function [8], which allows generation of the ECG signals of certain defined parameters and control a type and level of noise signal.

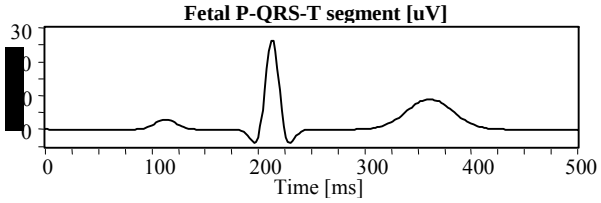

Figure 3: Modelled fetal PQRST segments using average values of amplitude and time parameters calculated between particular waves.

The following average amplitude-time relationships between particular waves were used to model the FECG signal: QRS amplitude = 30 [μV], QRS width = 50 [ms], PQ segment = 45 [ms], P amplitude = 10 [%QRS], P width = 56 [ms], ST segment = 70 [ms], T amplitude = 25 [%QRS], T width = 130 [ms]. The modelled signal fragment is shown in Figure 3.

The complete electrocardiogram originates from multiplication of the modelled cycles with a pre-set frequency. In this way, we have obtained a given value of the heart rate, which is determined on the basis of the RR intervals established between particular R waves. The heart rate is expressed in beats per minute (bpm) and is calculated according to the following equation:

$$FHR\,[bpm] = \frac{60000}{RR[ms]} \quad (11)$$

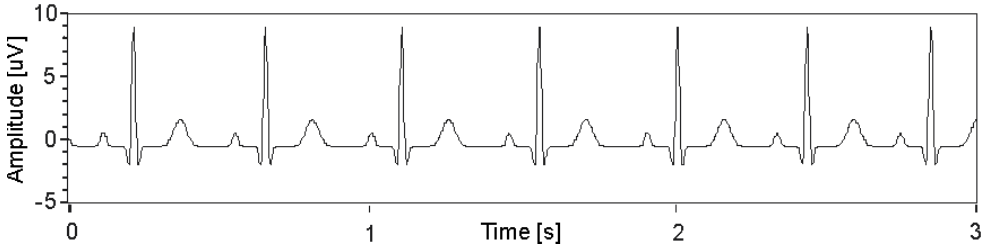

Figure 4: Artificial fetal electrocardiographic signals (sampling frequency = 500Hz, total duration time = 10min, FHR=140 bpm ± 10 bpm).

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The real fetal heart rate does not keep a constant value - it continuously changes. This feature has also been taken into account when modelling the artificial FECG signals. Apart from the possibility to establish the constant heart rate, there is also a possibility to describe the variability as a maximum value of oscillation around the established value (in the generation process three constant values of fetal heart rate were set: 100, 140, 180 bpm with oscillation varying in the range of ± 10 bpm). Using this range, the change of the heart rate value for each cardiac cycle is generated randomly. Figure 4 presents a fragment of the modelled fetal signal (total duration time is 10 min and the sampling frequency is 500 Hz). Generated signals together with all the characteristic parameters are stored in the signal database. So we have at our disposal complete information on the occurrence, duration and amplitude of particular waves.

For the procedure of generation of the artificial abdominal functions five constant SNR values were considered: 10, 5, 0, -5, -10 dB. The SNR coefficient was defined as:

$$\mathrm{SNR}\,[\mathrm{dB}] = 10 \cdot \log \frac{P_S}{P_N} \qquad (12)$$

where:
P_S – the power of fetal electrocardiogram,
P_N – the power of interferences.

For these established SNR values the particular types of interferences were modelled. The low-frequency interferences were modelled using the 0.5 Hz sinusoid waveform. The phase shift was a random value of the regular distribution from the range $<-\pi, +\pi>$. The power line interferences were modelled using 50 Hz sinusoid (the phase was also a random value). Modelling of the harmonic components of the power line interference was not performed because, in practice, the 50 Hz component is usually dominant. The muscular activity interferences were modelled by the Gaussian white noise. The uterine contractions were represented by the white noise that had been filtered in the frequency range 0.1 – 3 Hz and then amplitude modulated by the signal representing amplitude and the duration of the particular contractions. Additionally, complex abdominal signals with the resultant interference being a sum of all the modelled signals were also generated. Figure 5 show the exemplary signals generated for SNR = 0dB.

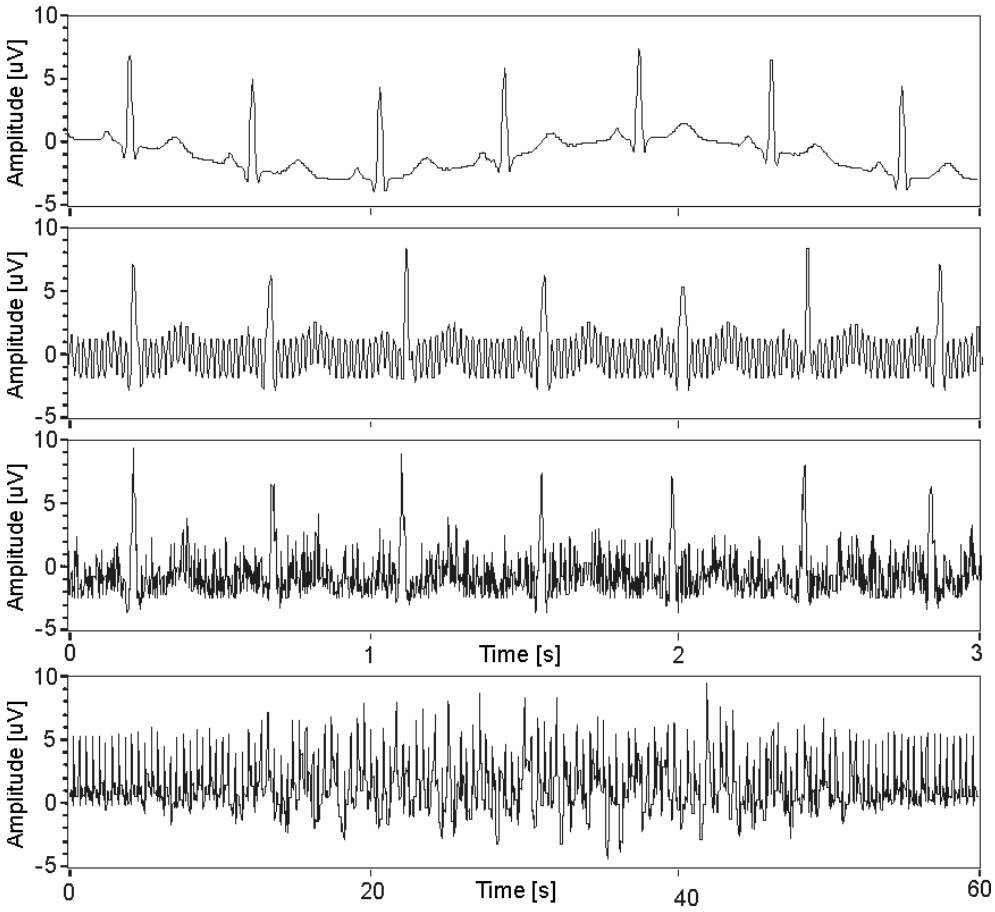

Figure 5: Modelled FECG signal together with the interferences (SNR equal to 0 dB): low-frequency, power line, muscular and the uterine contractions.

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Finally, the database has been collected which comprised 75 of FECG signals representing in true way both the shape of the FECG signal and the level and type of particular interferences occurring in fetal electrocardiography.

Results

Two different cases can be distinguished in the process of the detector efficiency evaluation:

- correct detections, e.g. detection of the QRS complex in the place where it has originally occurred (TP – true positive),
- incorrect detections, e.g. detection of the QRS complex in the place where it has not originally occurred (FP – false positive).

For all previously generated testing signals particular detection functions were determined, and then they were analyzed in a given decision stage. On the output of all these stages we obtained the vectors of fiducial points defining possible places of occurrence of particular fetal QRS complexes. By comparing obtained fiducial points with the reference ones, which were determined during the generation of FECG signal, the percentage coefficient (%TP) of correctly detected fetal QRS complexes in a given record as well as the number of incorrect detections (NFP) were calculated. In the work the correct detection of QRS complex was assumed if a given fiducial point FP(i) determined by detection algorithm was in the range: reference FP(i) ± 0.5 modelled QRS width. At the same time for a given algorithm the mean detection error (MDE) was calculated as well as the standard deviation which just defined a precision of QRS complexes (R waves) detection.

It appeared that the most efficient is the detection algorithm created with a help of detection function consisting of LO1 filter and nonlinear operation NO3. For this DF the larger mean value of the percentage coefficient was obtained (%TP = 98.1) for the worst record e.g. record with all the interferences of the highest level (SNR = -10dB). At the same time the lowest value of %TP equal to 97.1 was ensured by the simplest decision stage DS1. Adding of the next decision rules fed to slight increase of %TP and for example after the DS1A and DS1B rules were added the value of %TP increased to 98.5. However the highest value of %TP was achieved with the decision stage DS2, which uses composite decision rule analysing both acceptable physiological changes of fetal heart rate (in consecutive RR intervals) and changes of amplitude and shape of consecutive fetal QRS complexes. The mean number of incorrectly detected QRS complexes – NFP_{MD} in above FECG record also achieved the lowest value for the detection function consisting of LO1 and NO3, and was equal to 28, however for the decision stage DS2 it reached value of 10.

There were obtained slightly worse results for the detection algorithm based on detection function consisting of LO3 and nonlinear operation NO4. In this case the mean value of percentage coefficient of correctly detected fetal QRS complexes for the highest level of all modelled interferences was equal to 97.3% (the lowest value of %TP = 94.5 was obtained for DS1 and the highest %TP = 99.3 for DS2) and the mean number of incorrectly detected QRS complexes NFP_{MD} was 39, however for the decision stage DS2 the NFP = 16. At the same time for this particular function the highest precision of the QRS (R waves) detection was ensured – mean error MDE = 1.61 ± 1.94 [ms], while for the detection function LO1 + NO3 this error was MDE = 5.92 ± 3.04 [ms].

The worst results we obtained for the detection algorithm which used the detection function basing on the signal derivatives (LO2). This DF appeared to be very sensitive to muscle and powerline interferences which led to significant increase of the number of incorrectly detected fetal QRS complexes which independently on the decision stage applied was equal to 112 for records with the highest level of all modelled interferences. The mean value of percentage coefficient of correctly detected fetal QRS complexes for the considered records was 60.9 (the lowest value of %TP = 54.1 was obtained for DS1 and the highest %TP = 68.6 for DS2) and the error was MDE = 6.43 ± 6.08 [ms].

Conclusions

The performed tests of different algorithms of fetal QRS complexes detection confirmed the complexity and difficulty of their efficiency evaluation. It results mostly from a very low amplitude of FECG signal recorded on maternal abdomen and thus can be easily distorted by various types of noise signals. Particularly difficult to remove are the interferences of wide range of common frequencies and amplitude comparable and sometimes exceeding the amplitude of the useful signal (e.g. muscle interferences). Additional complication is caused by a lack of freely distributed signal database which could be used to testing of the algorithms for FECG analysis.

The test carried out by us showed that every single step of the detection process impacts on its efficiency with the same power: starting from the defining of the detection function, throughout the preliminary detection and ending on the selection and correct set of certain decision rules allowing recognition whether the detection function peak really corresponds to the fetal QRS complex.

The obtained results are required to be confirmed using the appropriate database of the real signals recorded from maternal abdomen. Currently, we are working on a collecting of such database with the particular attention paid on description of records by clinical experts e.g. founding by them the occurrences of correct QRS complexes. In the final step the tests should take into account the time and computational effort required by the particular algorithms which would help in the selection of the algorithm for the application in the on-line mode.

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References

[1] BERGVELD P., MEIJER W.J.H. (1981): 'A New Technique for the Suppression of the MECG', *IEEE Trans. Biomed. Eng.,* 28, pp. 348-354

[2] CALLAERTS D., DE MOOR B., VANDEWALLE J., SANSEN W. (1990): 'Comparison of SVD method to extract the fetal electrocardiogram from coetaneous electrode signals', *Med. Biological Eng. And Computing,* 28, pp. 217-224

[3] FRIESEN G. M., JANNETT T. C., JADALLAH M., A., YATES A., L., QUINT S., R., NAGLE H., T. (1990): 'A Comparison of the Noise Sensitivity of Nine QRS Detection Algorithms', *IEEE Trans. Biomed. Eng.,* 37, pp. 85-98

[4] VAN GEIJN H.P. (1980): 'Analysis of heart rate and beat-to-beat variability: Interval difference index', *Am. J. Obstet. Gynecol.,* 138, pp. 246-252

[5] KOHLER B. U., HENNIG C., ORGLMEISTER R. (2002): 'The Principles of Software QRS Detection – Reviewing and Comparing Algorithm for Detecting this Important ECG Waveform', *IEEE Eng. in Med. and Biol.,* 2, pp. 42-57

[6] KOTAS M. (1996): 'A new method of fetal QRS Detection', *Biocybernetics & Biomedical Engineering,* 16, pp.147-163

[7] LAI K. CH., SHYNK J. J. (2002): 'A Successive Cancellation Algorithm for Fetal Heart-Rate Estimation Using an Intrauterine ECG Signal', *IEEE Trans. Biomed. Eng.,* 49, pp.943- 954

[8] MATONIA A., JEZEWSKI J., KUPKA T., WROBEL J., HOROBA K. (2005): 'Modelling of Non-invasively Recorded Maternal and Fetal Electrocardiographic Signals', *Biocybernetics & Biomedical Engineering,* 25, pp. 27-39

[9] JEZEWSKI J., MATONIA A., KUPKA T., GACEK A., HOROBA K. (2002): 'Suppression of maternal ECG interference in abdominal fetal electrocardiogram', Proc. of IFMBE - The 12th Nordic Baltic Conf. on Biomed. Eng. and Med. Phys. Reykjavik, Iceland, 2002, pp. 162-163

[10] MATONIA A., JEZEWSKI J., KUPKA T., HOROBA K., WROBEL J. (2003): 'Algorithm for recognition and suppression of interfering maternal electrocardiography', Proc. of KOSYR - 3rd Conf. on Computer Recognition Systems, Miłków, Poland, 2003, pp. 55-61

[11] MATONIA A., KUPKA T., JEZEWSKI J., WROBEL J., GACEK A. (2005): 'Metody tłumienia sygnału EKG matki dla potrzeb nieinwazyjnej elektrokardiografii płodowej', Proc. of KBIB 2005 - XIV Krajowa Konferencja Naukowa „Biocybernetyka i Inżynieria Biomedyczna", Częstochowa, Poland, 2005, pp. 228-234

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