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The Maternal ECG Suppression Algorithm for Efficient Extraction of the Fetal ECG from Abdominal Signal

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Abstract **— At present, noninvasive recording of abdominal fetal electrocardiogram and analysis of the fetal heart rate variability seems to be the most promising method to detect the fetal hypoxia. The main problem is to obtain a good quality fetal ECG, which is strongly distorted by maternal component of dominating energy. The paper presents the new method of maternal electrocardiogram recognition and suppression relying on determination of template maternal PQRST complex and its subtraction during consecutive maternal cardiac cycles. The efficiency of the developed method was evaluated and related to three other selected methods for maternal ECG suppression using dedicated coefficients created for this comparison.**

I. Introduction

FETAL Heart Rate (FHR) analysis is widely used as an assessment of fetal wellbeing. The recording of electrical activity of fetal heart has obviously the potential to provide R-R intervals data with beat-to-beat accuracy. The crucial step in the noninvasive abdominal fetal electrocardiography is efficient suppression of the maternal electrocardiogram (MECG) which energy exceeds many times energy of the fetal electrocardiogram (FECG) [1], [2]. Inefficient suppression can affect the FECG shape and thus the detection of QRS complexes which in turn influences the determination of FHR signal. The simple filtration is useless since the frequency band of MECG and FECG overlap [3]. Additionally, a lack of freely distributed database of the reference signals (like in case of adults) makes the validation of the suppression methods very difficult.

There are many methods for maternal electrocardiogram suppression, which are based on: adaptive filtration [4], autocorrelation and crosscorrelation as well as weighted summation of abdominal signals [5] or spatial filtration [6], [7]. Their main disadvantage is the necessity to record a great number of abdominal signals and sometimes also additional chest signals. These methods often require strictly determined placement of electrodes on patient's body (e.g. in order to ensure appropriate polarization of MECG signals) that is usually difficult to fulfill during labour. This work presents an alternative method which overcomes the mentioned disadvantages. Evaluation of its efficiency and comparison with few selected methods was carried out.

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II. Methodology

A The algorithm for MECG suppression

Each electrical signal recorded on maternal abdomen surface contains three components:

$$x(t) = x_M(t) + x_F(t) + x_N(t) \quad (1)$$

where: $x_M(t)$ – maternal electrocardiogram, $x_F(t)$ – fetal electrocardiogram, $x_N(t)$ – interferences coming from different sources (e.g. muscle activity, power line).

If the template PQRST complex is established the MECG signal can be represented as:

$$x_M(t) = \sum_i \{a_i \cdot PQRST + d_i\}(t - t_i) \quad (2)$$

where: a_i – factor describing an amplitude change of the *i-th* PQRST complex in relation to the template, d_i – component describing a shape change of the *i-th* complex in relation to the template, t_i – fiducial point indicating R-wave in the *i-th* complex.

In general, the proposed method for maternal ECG suppression comprises the following steps: determination of the fiducial points t_i, determination of the template PQRST complex by averaging of a set number of adequate complexes, determination of a_i factors and subtraction of the template from abdominal signal in the fiducial points. With additional assumption that all maternal heart contractions are caused by the same type of excitation ($d_i = 0$), the appropriate realization of all above steps provides to complete suppression of the MECG in the abdominal signal, e.g.:

$$x_F(t) + x_N(t) = x(t) - \sum_i a_i \cdot PQRST(t - t_i) \quad (3)$$

During subtraction process, the template PQRST and the successive complex can be synchronized in time by means of the correlation function. It prevents from a shift between them, when some noise components occur. However, due to digital representation of the signals being processed, there can be still a shift between fiducial points which can reach the value of the sampling period. This affects mainly the suppression of fast wave constituting the QRS complex and may leave some residual component. Since this component is a result of the difference between two almost identical QRS complexes shifted by one sample, it is the first derivative of the QRS complex and it can be subtracted in the next step. By analogy with template PQRST complex, the factor (b_i) that enables appropriate fitting of the amplitude should be set for derivative of QRS complex [8]. Finally, the MECG suppression process can be described as:

$$x_F(n) + x_N(n) = x(n) - \sum_i \{ a_i \cdot PQRST \}(n - n_i) - \sum_i \{ b_i \cdot dQRS \}(n - n_i) \quad (4)$$

where: *dQRS* – the derivative of the template QRS complex, n_i – fiducial point of the *i-th* QRS complex.

Taking into account that energy of the QRS complex is much higher than energy of the P and T waves, the a_i factor are estimated as follows:

$$a_i = \frac{\sum_{m=-\frac{w}{2}}^{m=\frac{w}{2}} QRS(m) \cdot x(n + n_i + m)}{\sum_{m=-\frac{w}{2}}^{m=\frac{w}{2}} QRS^2(m)} \quad (5)$$

where: w – width of the template QRS complex.

After that, the template QRS complex modified by determined factor is subtracted from abdominal signal in the fiducial points, and the following signal is obtained:

$$x_1(n) = x(n) - \sum_i a_i \cdot PQRST(n - n_i) \quad (6)$$

The b_i factors are determined just like the a_i factors but here the input signal is the $x_1(n)$:

$$b_i = \frac{\sum_{m=-\frac{w}{2}}^{m=\frac{w}{2}} dQRS(m) \cdot x_1(n + n_i + m)}{\sum_{m=-\frac{w}{2}}^{m=\frac{w}{2}} dQRS^2(m)} \quad (7)$$

In real signals the coincidence of maternal and fetal complexes can occur which can cause false determination of fiducial points (n_i) of the maternal complexes as well as factors a_i and b_i. Therefore, in the developed method the procedures minimizing the influence of above mentioned phenomena are applied as described below.

Abdominal signals after preliminary high-pass filtration are used to establish auxiliary signal *s(n)* with Generalized Singular Value Decomposition (GSVD) technique [6]. In the *s(n)* signal the energy of MECG is maximized, whereas the energy of FECG as well as any other noise is minimized. In this way, *s(n)* signal containing exclusively maternal electrocardiogram is obtained [7]. It enables precise detection of maternal QRS complexes (fiducial points n_i) which consequently minimizes the synchronization error. Since this error is responsible for occurrence of the residual component (the derivative of the QRS) the b_i factors are determined in this step. They are calculated using the equations (5) and (7) where abdominal signal *x(n)* is replaced by the signal *s(n)*.

In the next step, the subtraction operations are performed over all abdominal signals but their order is reversed. At first, a derivative of template QRS complex is subtracted. Since the fiducial points determined precisely using the *s(n)* signal are used for all abdominal signals, the b_i factors estimated using the *s(n)* are also applied in all abdominal signals.

$$x_{2,k}(n) = x_k(n) - \sum_i b_i \cdot dQRS_k(n - n_i) \quad (8)$$

where: k – the number of the abdominal signals recorded.

Then the a_i factors are estimated according to (5) for each abdominal signal individually, which enables subtraction of the modified template QRS complex and finally leads to the MECG suppression in each abdominal signal:

$$x_{F,k}(n) + x_{N,k}(n) = x_{2,k}(n) - \sum_i a_{k,i} \cdot PQRST_k(n - n_i) \quad (9)$$

B Validation procedures

In the signal recorded from maternal abdomen the noise component consists of: low frequency, muscle activity and power line interferences. In the process of evaluation of the maternal ECG suppression methods the rest maternal component and other noise signal were considered separately (Fig. 1). This made possible to evaluate the efficiency of the maternal suppression and the influence of a given method on the noise level.

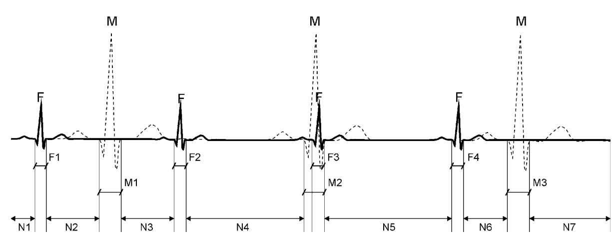

Fig. 1. The abdominal signal segments taking a part in the determination of mean power of: the noise component (muscle activity): N=N1+N2+N3+N4+N5+N6+N7, the FECG signal: F=F1+F2+F4, the rest MECG signal: M=M1+M3.

Since the power of P and T waves of both fetal and maternal electrocardiogram is low in comparison to QRS complex, the mean noise power is equal to the mean signal power calculated in the segments outside the maternal and fetal QRS complexes.

The following coefficients have been defined on a basis of mean power values:

- coefficient CM describing the level of the rest MECG:

$$CM = 10 \cdot \log \frac{PF}{PM} \tag{10}$$

- coefficient CN describing the quality of the FECG (suppression of muscle interferences):

$$CN = 10 \cdot \log \frac{PF}{PN} \tag{11}$$

where: PF – the mean power of the detected fetal QRS complexes being separated from maternal complexes (calculated in F1, F2, F4), PM – the mean power of detected maternal QRS complexes being separated from fetal complexes (calculated in M1, M3), PN – the noise mean power.

The unwanted effect of the application of a given suppression method is the possible change of fetal QRS shape which usually has significant influence on the further QRS complex detection. The less these changes are the more stable detection function is obtained which increase the efficiency of the detection algorithm [3], [2].

In order to evaluate the QRS distortion we define the coefficient CE:

$$CE = \frac{\sqrt{\frac{1}{I-1} \cdot \sum_{i=1}^{I-1} \left(r_{i+1} - r_i\right)^2}}{\frac{1}{I} \cdot \sum_{i=1}^{I} r_i} \tag{12}$$

where: I – the number of all fetal QRS complexes detected, r_i – factor estimating a change of amplitude of the *i-th* complex in relation to the amplitude of the averaged one.

The factor r_i is defined by:

$$r_i = \frac{\sum_{k=-\frac{S_F}{2}}^{k=\frac{S_F}{2}} \left\{FQRS_{AVG}(k)\right\} \cdot \left\{FQRS_i(k)\right\}}{\sum_{k=-\frac{S_F}{2}}^{k=\frac{S_F}{2}} \left\{FQRS_{AVG}(k)\right\}^2} \tag{13}$$

where: i – the number of consecutive fetal QRS complexes (FQRS), S_F – the width of FQRS (set at 50 ms = 20 samples), $FQRS_{AVG}$ – the averaged fetal QRS complex, it is determined using only these fetal QRS complexes which are separated from maternal complexes.

III. Results

Comparison study concerning the suppression methods was performed using three records. Each of them consists of four signals recorded from maternal abdomen between 36th and 40th week of gestation with the use of electrode placement proposed in [5]. These signals were preliminary processed with high-pass digital filter to remove strong low frequency interferences present in almost all collected abdominal signals. Different level of other noise signal (mainly muscle activity) and a wide range of FECG amplitude were noted in the records.

Two suppression methods were implemented as a reference for the method being developed. The first (M1) method proposed by Bergveld and Meijer [5] relies on weighted summation of abdominal signals. Weighted coefficients are determined using the Hildreth d'Esopo optimization algorithm, where during iteration process the coefficients undergo the changes so as to minimize the MECG but with keeping the FECG unchanged. This method requires strictly determined placement of leads on the abdominal wall. The second method (M2) was described by Callaerts et al. [6]. It is based on spatial filtration combined with singular value decomposition technique (SVD).

For each testing record the FECG signals were determined with a help of three MECG suppression methods (Fig. 2), and then the coefficients evaluating their efficiency were calculated. The method based on weighted summation (M1) produces only one FECG signal for each four-signal set. The method relying on spatial filtration (M2) allows estimation of FECG signal in particular leads but only with large number of abdominal leads. In our study, where four leads were applied this method provided only one FECG signal. The method developed by us (M3) is also able to determine FECG signal in every abdominal signal, but for the comparison study the one FECG was selected. The additional method which was created by removing from the M3 the stage of QRS derivative subtraction was included to the study and named M4. The mean values of the coefficients obtained for all records are presented in Tab. I.

TABLE I
MEAN VALUES OF COEFFICIENTS

	M 1	M 2	M 3	M 4
CM_M [dB]	15.53	17.80	22.04	9.86
CN_M [dB]	13.26	13.27	9.98	9.63
CE_M	0.09	0.14	0.09	0.23

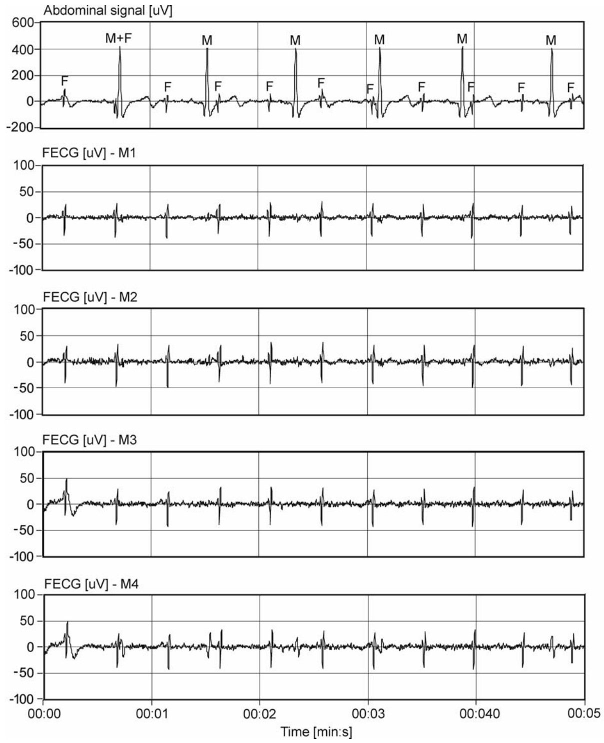

Fig. 2. The result of application of the MECG suppression methods using the exemplary abdominal signal.

The subtraction of the template only (M4) does not provide satisfactory result (CM_M = 9.86 dB – the lowest value). Such simplifying of the developed suppression method is responsible for remaining the quite significant rest component which relates to the fast changing maternal QRS complex. This rest component can be removed just by subtraction of the QRS derivative which can be clearly seen in the results. The method M2 suppresses the MECG signal also with quite high efficiency (CM_M = 17.80 dB). The unsatisfactory efficiency to remove the other noise signals has been found for the method M3 (CN_M = 9,98 dB), whereas the methods M1 and M2 ensured better results – the coefficients describing this efficiency reached 13.27 dB. This weakness of our method is caused by the processing of only these fragments in abdominal signals which relate to the particular maternal cardiac cycles. The other fragments are not taken into account and thus the noise components in them are not suppressed. As for the distortion of the fetal QRS complex which can be caused by the MECG suppression the method based on weighted summation of abdominal signals (M1) and the method M3 appeared to have the lowest influence – CE_M = 0.09.

IV. Conclusions

In this work the new method for suppression of MECG component is presented, which relies on subtraction of the template maternal PQRST complex and QRS complex derivative. The efficiency of this method was estimated in relation to three other representative methods. The coefficients created especially for this comparison were used which describe both efficiency of the noise signal suppression and the distortion of fetal QRS complexes.

In general, the obtained results confirm high usability of the methods considered. The maternal electrocardiogram suppression method proposed in this paper requires neither strictly determined location of measurement electrodes nor additional chest signals. Achieved results show that this method allows complete suppression of MECG signal without influence on FECG signal. The weakness of this method is the unsatisfactory suppression of the other noise components originating mainly from abdominal muscle activity. This kind of noise can be removed by additional method, for example, already mentioned in this paper the spatial filtration technique, where the input signals are FECG signals obtained after subtraction of the template maternal PQRST complex and QRS complex derivative.

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