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Citation for published version (APA):

Vullings, R., Peters, C. H. L., Mischi, M., Sluijter, R. J., Oei, S. G., & Bergmans, J. W. M. (2010). Artifact reduction in maternal abdominal ECG recordings for fetal ECG estimation. In *Proceedings of the 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society 2007, EMBS 2007, 22 - 26 August 2007, Lyon, France* (pp. 43-46). Institute of Electrical and Electronics Engineers.
<https://doi.org/10.1109/IEMBS.2007.4352218>

DOI:

[10.1109/IEMBS.2007.4352218](https://doi.org/10.1109/IEMBS.2007.4352218)

Document status and date:

Published: 01/01/2010

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Artifact reduction in maternal abdominal ECG recordings for fetal ECG estimation

Rik Vullings, Chris Peters, Massimo Mischi, Rob Sluijter, Guid Oei, and Jan Bergmans

Abstract—Monitoring the fetal electrocardiogram (fECG) is currently one of the most promising methods to assess fetal health. However, the main problem associated with this method is that the signals recorded from the maternal abdomen are affected by noise and interferences: the maternal electrocardiogram (mECG) being the dominant interference. In this paper a mECG removal technique is described, which is based on dynamic segmentation of the mECG and subsequent linear prediction of the mECG segments. Moreover, as the linear prediction is significantly affected by artifacts, a signal validation technique is presented to suppress the effect of artifacts on the mECG prediction. The performance of the presented technique is evaluated by comparison to the performance of three other mECG removal techniques: the presented technique outperforms the other techniques for all recordings.

I. INTRODUCTION

Monitoring the fetal heart rate (fHR) and fetal electrocardiogram (fECG) in antenatal abdominal recordings is important to assess the fetal condition. The fHR variability provides physicians with information on the ability of the fetus to adapt to temporal oxygen deficiency and increments in the intra-uterine pressure. Moreover, the temporal and morphological parameters of the fECG provide additional information on fetal growth and its physiological condition [1].

The most widespread method to monitor the fHR is by means of Doppler ultrasound. This method is, however, associated with inaccuracies due to the fact that the ultrasound probe requires frequent repositioning because of fetal movement. In addition, the information provided by the fHR has a relatively low positive predictive value: it is only definite when the fetal condition is clearly good or clearly bad [2]. For the situations in-between, the fECG could provide additional information to assess the fetal condition.

During labor, the fECG can be recorded by means of an electrode positioned directly on the fetus. This method is invasive and can only be applied when the fetal membranes have ruptured. Antepartum, the fECG can be monitored using contact electrodes positioned on the maternal abdomen. The signals recorded by these electrodes, however, are a mixture of electrophysiological signals, including the fECG, the maternal electrocardiogram (mECG), powerline interference from the electricity grid, and motion artifacts.

Since the spectral properties of the powerline interference and the motion artifacts differ from the spectral properties of the mECG and fECG, these interferences can be suppressed by frequency selective filtering. In contrast, the spectral properties of the fECG and mECG overlap and as a result these signals cannot be separated by filtering [3].

Several techniques to remove the mECG from antenatal abdominal recordings have been proposed in literature. One of the most frequently used classes of techniques, is the class of techniques that are based on template subtraction [4], [5], [6]. In general, template subtraction techniques operate by generating a template of the mECG and subtracting this template from each individual mECG complex. Prior to subtraction, the template is often dynamically scaled to improve the resemblance to the individual mECG complex [4]. This approach is based on the assumption of (quasi-)stationary behavior of the mECG. However, since the positions of the abdominal electrodes with respect to the position and orientation of the maternal heart continuously fluctuate as a result of respiratory induced motion of the abdominal wall, the mECG not only varies in amplitude but also in morphology. As a consequence of this morphological variability, adaptation of the amplitude of the template alone does not result in a sufficiently accurate mECG removal.

This problem can be solved by dividing each mECG complex into separate segments and generating a dynamically scaled template for each segment [5], [6]. By scaling each segment individually, variations in the morphology of the mECG can be dealt with accurately. Moreover, the accuracy of the mECG removal can be further improved by scaling, time-aligning and offset-compensating the different mECG segments prior to generating the template [6].

The segmentation of the mECG complexes into separate waves, however, has a significant disadvantage. When a particular mECG segment is corrupted by an artifact or – more likely in the case of antenatal abdominal recordings – a fetal ECG complex, this artifact affects the calculation of the scaling parameter. Without segmentation, the influence of this artifact would be smaller as the percentage of samples corrupted by the artifact is smaller. In short, the use of segmentation for template based mECG removal techniques implies a trade-off between accuracy and artifact sensitivity.

In this paper, a signal validation technique is presented that overcomes this trade-off. By detecting artifacts in the mECG before calculating the scaling parameters, the samples that are corrupted by artifacts can be excluded from the parameter calculation. Consequently, the advantage of improved accuracy by mECG segmentation is retained, whereas

This work was supported by the Dutch Technology Foundation STW
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the disadvantage of increased sensitivity to artifacts has disappeared. This signal validation technique is incorporated in the mECG subtraction technique of [6]. This mECG subtraction technique is referred to as the weighted averaging of mECG segments (WAMES) and operates by the dynamic segmentation of the mECG and the consecutive estimation of the mECG segments by linear prediction of time-aligned, scaled, and offset-compensated segments from preceding mECG complexes.

The ideal manner to evaluate this signal validation technique is by comparing the performance of WAMES in mECG removal from antenatal abdominal recordings to the performance of several other techniques and to the performance of WAMES without employing signal validation. Unfortunately, it is impossible to assess the absolute performance in estimating the mECG, as the mECG in antenatal abdominal recordings is corrupted by artifacts and interferences and therefore unknown. Nevertheless, to approximate the absolute performance, the techniques are applied on modeled recordings, consisting of the superposition of an abdominal mECG signal recorded from a non-pregnant subject, a fECG signal recorded by an electrode positioned on the fetal scalp during labor, and a Gaussian noise source.

II. MODELING ANTENATAL ABDOMINAL RECORDINGS

The abdominal recordings are conducted with a M-PAQ amplifier (Maastricht Instruments Ltd., the Netherlands) with a gain of 500 and a sampling frequency of 1 kHz. The adopted electrode configuration consists of eight unipolar contact electrodes on the maternal abdomen with a common reference positioned near the umbilicus.

Ten 8-channel abdominal recordings of 60 seconds each are performed on a non-pregnant subject. Antenatal abdominal recordings are subsequently modeled by superimposing a fECG signal recorded from a fetal scalp and a Gaussian noise signal to these signals. Several amplitude ratios between the mECG, the fECG, and the noise are used as to model several gestational ages and noise environments. The adopted amplitude ratios between the mECG and the fECG range from 5 dB to 13 dB and the amplitude ratios between the mECG and the noise range from 7 dB to 17 dB.

III. SIGNAL VALIDATION FOR ARTIFACT REDUCTION

As stated previously, the use of segmentation in template based mECG estimation techniques implies a trade-off between accuracy and sensitivity to artifacts. The sensitivity of the technique to artifacts can, however, be decreased by employing a signal validation technique to exclude the samples corrupted by artifacts from further calculations.

Since the fECG is the most frequently encountered artifact in antenatal abdominal mECG recordings, the signal validation technique is mainly focussed on the detection of fECG complexes in the mECG segments. As the fECG and mECG are not correlated, averaging several consecutive mECG segments results in a template of the mECG segment with

Fig. 1. (a) mECG segment corrupted by a fECG complex (solid) and the mECG segment template generated by averaging several consecutive mECG segments (dotted). (b) The difference between the corrupted mECG segment and the template (solid), the filtered difference function δ (dotted), and the threshold for detecting possible artifacts or fECG complexes (dashed). The samples that are detected as being corrupted are indicated by the shaded area.

a reduced or even negligible fECG contribution. However, when this template is used to estimate a mECG segment that is corrupted by a fECG complex, the calculation of scaling parameters is affected by this artifact.

Nevertheless, by comparing the morphology of the template to the morphology of an individual mECG segment, the presence of a fECG complex in this individual segment can be detected. This is illustrated in Fig. 1(a) and 1(b). Because the sign of the difference between the template and the individual segment is a priori unknown and because the fECG complex corrupts several consecutive samples, a running average filter is applied on the squared difference function

$$\delta_i = \sum_{j=0}^L (Z_{i-j} - \bar{Z}_{i-j})^2, \quad (1)$$

with δ the output of the running average filter, $\bar{Z}$ the template, Z the individual segment, and L the width of the filter. The indices i and j represent the indices for the output of the running average filter and for indicating each sample within the filter window, respectively. This width is based on a physiological model of the fECG and it is chosen to match the width of the fECG complex.

A localized maximum in δ now indicates the presence of a fECG complex and hence determines which samples are corrupted and have to be excluded from further calculations. These samples are defined as the samples exceeding a certain threshold. The amplitude of this threshold is set as a percentage of the mECG power, in order to avoid problems for mECG signals with large either small power. This threshold can be seen in Fig. 1(b).

IV. MATERNAL ECG REMOVAL TECHNIQUES

A. WAMES

As stated previously, WAMES operates in two steps. In the first step the mECG complexes are dynamically segmented and in the second step, each of these segments is estimated by linear prediction. This linear prediction is performed using time-aligned, scaled, and offset-compensated corresponding segments from preceding mECG complexes. This method is described in more detail in [6] but it is discussed briefly in

Fig. 2. Nomenclature of the ECG.

this paper to illustrate the utilization of the signal validation technique.

1) *Dynamic maternal ECG segmentation:* Commonly, ECG complexes consist of a P-wave, a QRS-complex, and a T-wave (Fig. 2). The P-wave is associated with the depolarization of the atria. The QRS-complex, which can be subdivided into a separate Q-wave, R-wave, and S-wave, is associated with the depolarization of the ventricles. Finally, the T-wave is associated with the repolarization of the ventricles.

The segmentation by WAMES is based on these waves, i.e. each of these waves represents an individual segment. The start and end of each wave is detected by means of windowing and adaptive thresholding. Based on a physiological model, a window is defined for each wave in which this wave is expected to be present. Next, an adaptive threshold is defined within this window to determine the start and end of the wave.

The parts of the ECG complex that are not included in one of these segments are referred to as isoelectrical periods, i.e. periods in which the electrical activity of the heart is constant.

2) *Linear prediction:* Each segment in the mECG is estimated by linear prediction, i.e. the weighted averaging of N corresponding segments from preceding mECG complexes. The mECG segment that is estimated is represented by $Z_{i,j}$, with $Z = \{P, Q, R, S, T, iso\}$, i the index of the mECG complex to which the segment belongs, and j the index of the samples within the segment. The N segments that are used in the weighted averaging can therefore be represented by $Z_{i-k,j}$, with $1 \leq k \leq N$ indicating which preceding mECG segment is used.

Prior to averaging, the segments $Z_{i-k,j}$ are scaled, time-shifted, and offset-compensated to minimize the difference with $Z_{i,j}$

$$\tilde{Z}_{i-k,j} = aZ_{i-k,j+b} + c \quad a, b, c \in \mathbb{R}, \quad (2)$$

with a the scaling parameter, b the time-shift, and c the offset. The optimal parameters $\hat{a}$, $\hat{b}$, and $\hat{c}$ are calculated by minimizing the mean squared error between $\tilde{Z}_{i-k,j}$ and $Z_{i,j}$

$$\vec{\nabla} \left(\frac{1}{M} \sum_{j \in F_{i-k}} (Z_{i,j} - \tilde{Z}_{i-k,j})^2 \right) = \vec{0}, \quad (3)$$

with $\vec{\nabla}$ representing the gradient $\left(\frac{\partial}{\partial a}, \frac{\partial}{\partial b}, \frac{\partial}{\partial c} \right)$. Here F_{i-k} is the set of samples that do not contain artifacts or fECG complexes and M is the number of samples included in F_{i-k} .

As stated previously, the scaled, time-aligned, and offset-compensated mECG segments $\tilde{Z}_{i-k,j}$ are linearly combined to determine an estimate for $Z_{i,j}$. The weights of this linear combination are given by the reciprocals of the mean squared errors between $Z_{i,j}$ and $\tilde{Z}_{i-k,j}$

$$w_{i-k} = \left(\frac{1}{M} \sum_{j \in F_{i-k}} (Z_{i,j} - \tilde{Z}_{i-k,j})^2 \right)^{-1}. \quad (4)$$

The estimated mECG segments $\hat{Z}_{i,j}$ can then be calculated by

$$\hat{Z}_{i,j} = \frac{\sum w_{i-k} \tilde{Z}_{i-k,j}}{\sum w_{i-k}}. \quad (5)$$

Finally, the template for the mECG complexes is generated by combining the templates for the individual mECG segments.

B. Reference techniques

Three reference techniques are implemented for the evaluation of WAMES. The first technique is proposed by Widrow et al. [7] and extended by Strobach et al. [8] and is based on adaptive noise cancellation using an artificial reference signal. This artificial reference signal is built from mECG templates that are generated by averaging several consecutive mECG complexes, synchronized on the QRS-complex. This technique is referred to as event-synchronous adaptive interference cancelling (ESAIC) [8].

The second technique is proposed by Ungureanu et al. [5] and is based on the adaptive scaling of individual segments of the mECG template to improve the resemblance to the mECG complex that is estimated. This mECG template is generated by averaging several consecutive mECG complexes that are synchronized on the QRS-complex. Therefore, this technique is referred to as event-synchronous interference cancelling (ESC) [5].

The third technique is proposed by Bergveld and Meijer [9] and is based on the spatial filtering of abdominal recordings. The mECG signal recorded by a particular electrode is estimated by linearly combining the mECG signals recorded by the other electrodes. The weights used in this linear combination are optimized by the method of Hildreth and d'Esopo.

WAMES and the technique proposed by Ungureanu et al. might appear to be similar to some extent. However, the main differences between WAMES and this technique are that in WAMES scaling is performed on the individual mECG segments rather than on the template segments. Moreover, in WAMES each segment is individually time-aligned, resulting in a more accurate mECG estimate in the event of varying time delays between the individual ECG waves.

V. RESULTS

The performance of WAMES in estimating the mECG in the modeled antenatal abdominal recordings is compared to the performance of ESAIC, ESC, spatial filtering, and WAMES without employing the signal validation technique. The performance is assessed by the normalized squared error

Fig. 3. Results of mECG subtraction by spatial filtering, ESAIC, ESC, WAMES, and WAMES without using the signal validation technique. The upper graph shows the modeled antenatal abdominal recording and the bottom graph shows the fECG signal used in modeled recording.

Fig. 4. Normalized mean squared error between the mECG used in the modeled antenatal abdominal recording and the estimate of this mECG for different mECG to noise amplitude ratios. The values of ϵ are obtained by averaging over all mECG to fECG amplitude ratios.

ϵ between the mECG signal used in the modeled recordings S and the estimate of this mECG signal by the various techniques $\hat{S}$

$$\epsilon = \frac{\sum_n (S_n - \hat{S}_n)^2}{\sum_n (S_n)^2}. \quad (6)$$

Fig. 3 shows a modeled antenatal abdominal recording and the signals resulting from the subtraction of the mECG by the different techniques. The depicted signals comprise 3 seconds of a 60 second recording. Fig. 4 and Fig. 5 show ϵ for different amplitude ratios between the mECG, the fECG, and the noise.

VI. DISCUSSION AND CONCLUSIONS

In this paper a signal validation technique is presented, which can be used for reducing the sensitivity to artifacts of mECG removal techniques. The technique is incorporated in WAMES, a mECG removal technique operating by dynamic

Fig. 5. Normalized mean squared error between the mECG used in the modeled antenatal abdominal recording and the estimate of this mECG for different mECG to fECG amplitude ratios. The values of ϵ are obtained by averaging over all mECG to noise amplitude ratios.

segmentation of the mECG and subsequent linear prediction of the mECG segments.

To assess the contribution of the signal validation technique to the performance of WAMES, WAMES is applied on modeled antenatal abdominal recordings twice: once with the signal validation technique and once without this technique. Moreover, the performance of WAMES in estimating the mECG in the abdominal recordings is assessed by comparing it to the performance of several other techniques on the same recordings.

Fig. 4 and Fig. 5 show that the signal validation technique significantly contributes to the performance of WAMES in estimating the mECG. When the signal validation technique is not employed WAMES performs similar to ESC and ESAIC, whereas when the signal validation technique is employed WAMES outperforms the reference techniques.

Future research is focused on the extraction of the fECG from antenatal abdominal recordings and analysis of this fECG for clinical assessments.

REFERENCES

- [1] K. Greene et al., Changes in the ST waveform of the fetal lamb electrocardiogram with hypoxemia, *Am J Obstet Gynecol.*, vol.144, Dec. 1982, pp 950–958.
- [2] I. Amer-Wählin et al., Cardiotocography only versus cardiotocography plus ST analysis of fetal electrocardiogram for intrapartum fetal monitoring: a Swedish randomised controlled trial, *Lancet*, vol. 358, 2001, pp 534–538.
- [3] S. Abboud and D. Sadeh, Spectral Analysis of the Fetal Electrocardiogram, *Comput Biol Med.*, vol. 19, 1989, pp 409–415.
- [4] S. Cerutti et al., Variability analysis of fetal heart rate signals as obtained from abdominal electrocardiographic recordings, *J. Perinat. Med.*, vol.14, no.6, 1986, pp 445–452.
- [5] M. Ungureanu and W. Wolf, Basic aspects concerning the event-synchronous interference canceller, *IEEE Trans Biomed Eng.*, vol.53, no.11, Nov. 2006, pp 2240–2247.
- [6] R. Vullings et al., Maternal ECG removal from non-invasive fetal ECG recordings, in *Proc. of IEEE EMBC*, New York, USA, 2006, pp 1394–1397.
- [7] B. Widrow et al., Adaptive noise cancelling: principles and applications, *Proc. IEEE*, vol.62, Dec. 1975, pp 1692–1716.
- [8] P. Strobach et al., Event-synchronous cancellation of the heart interference in biomedical signals, *IEEE Trans Biomed Eng.*, vol.41, no.4, Apr. 1994, pp 343–350.
- [9] P. Bergveld and W. Meijer, New technique for the suppression of the MEGG, *IEEE Trans Biomed Eng.*, vol. 28, 1981.