The event synchronous canceller algorithm removes maternal ECG from abdominal signals without affecting the fetal ECG

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Fetal monitoring using abdominally recorded signals (ADS) allows physicians to detect occurring changes in the well-being state of the fetus from the beginning of pregnancy. Mainly based on the fetal electrocardiogram (fECG), it provides the long-term fetal heart rate (fHR) and assessment of the fetal QRS morphology. But the fECG component in ADS is obscured by the maternal ECG (mECG), thus removal of the mECG from ADS improves fECG analysis. This study demonstrates the performance of the event-synchronous interference canceller (ESC) in mECG removal from ADS data, recorded during pregnancy and labor. Its advantage as a compensation method for extended ADS processing is discussed.

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1. Introduction

Fetal monitoring through evaluating the abdominal signals (ADS) allows the screening of the fetal well-being state, based on the analysis of the fetal heart rate (fHR) and of the waveform of the fetal ECG (fECG) [1]. The latter implies a strong advantage of this noninvasive recording method for fetal monitoring in comparison to methods like Doppler ultrasound [2]. But the main problem in extracting fECG from ADS is that the ADS contains several other disturbing signals besides the fECG which have higher amplitudes than the fECG and, in addition, are overlapping with it in the spectral domain. Some very recent publications [3–6] underline that this topic currently attracts huge research efforts.

Among the “noise” signals in ADS, the maternal ECG (mECG) is clearly the most salient source of disturbance, since its R-peak shows amplitudes being 2–10 times greater than the amplitude of the fetal R-peak [7]. The fECG R-peak amplitude ranges from 10 to 100 μV [8]; it depends on the electrode configuration and varies due to the different body weight and size of the mother and due to the different positions of the fetus within the uterus. Other less disturbing signals which must be considered are the electronic noise (introduced by amplifiers, etc.), the baseline wander of signals, the myoelectric crosstalk from abdominal muscles, and the uterine activity, especially during labor. In addition, the access to the fECG changes with time, especially with the appearance of the vernix in the last three months of pregnancy, when conduction pathways between the fetal heart pace and the maternal abdomen are reduced from global radial propagation to some preferential directions [9]; then even the R-peak of the fECG is hardly detectable [10]. Obviously, any (even small) improvement in ADS processing for fECG extraction represents a step forward to overcome this difficulty.

Several methods have been proposed to extract the fECG from ADS for fHR analysis, such as principal component analysis [11], independent component analysis [12] and nonlinear projective filtering [13], but the increasing interest of physicians to consider not only the instantaneous fHR but also the waveform of the fECG introduces new requirements for preserving the fECG morphology in ADS processing, thus linear filtering methods in general are getting more focused. For example, adaptive noise canceling using standard mECG recordings in addition [14] and the event-synchronous interference canceller (ESC) method [15,16] are appropriate candidates for removing the mECG from ADS to enhance the fECG. Here, the ESC approach which was previously [16] evaluated only on the DaISy [17] abdominal channel having the highest amplitude of the fECG (first abdominal channel) will now be evaluated on real data with
different morphologies recorded during pregnancy and labor, comprising also the second channel of the DaISy dataset [17] showing a small fetal QRS as compared with the maternal QRS, with an amplitude of about the same value as the amplitude of the maternal T-wave, in order to have included a well known dataset available to the research community. Finally, the performance of the ESC algorithm is discussed, in particular as a possible preprocessing method applied before any extended computerized fECG analysis for detailed fECG morphology evaluation.

2. Fetal ECG enhancement by the event-synchronous interference canceller (ESC) application

The classical adaptive noise canceller (Fig. 1a) removes a disturbing crosstalk signal from the signal of interest, under the assumptions that the signal of interest, $s(n)$, is not correlated with the noise source, $v_0(n)$, and that a version of the noise source is available through another recording channel, $v_1(n)$, which is used as a reference signal in this adaptive noise canceling concept. These conditions allow to estimate the crosstalk transfer function $S(\omega)$, which in turn can be used to establish an estimation $\hat{v}_0(n)$ of the crosstalk component and to subtract it from the recorded signal. When the noise source is a repetitive signal, the adaptive filter in Fig. 1a can be substituted through constructing an artificial version of the noise by repetition of the noise “period”, which results in the scheme of the event-synchronous interference canceller (ESC) shown in Fig. 1b [16]. ESC is a canceling method that removes a repetitive disturbing signal by adaptive subtraction of a cycle template; it can use an additional recording channel, $v_1$, which contains the noise at its source location almost isolated in order to obtain a trigger indicator for the repetition cycle. This indicator serves to cut the “noisy” segments (containing the mECG beat) from the recorded signal which are then averaged to build the mECG template $v_0$. This scheme bypasses the assumption of linearity for the propagation of the noise signal $v(n)$ to the recording site of $y(n)$.

For this study, however, this extra channel is not implemented but the shortcut between $y(n)$ and $v_1(n)$ is selected (Fig. 1b); thus, event detection for mECG beat is simply done using R-peak detection in $y(n)$ by thresholding. For removing signal wander and improving fECG extraction, the ADS are preprocessed by applying high pass filtering with a cutoff frequency of 2 Hz. If there is strong power line interference, then application of some power line rejection (e.g., [18,19]) must be included.

The subtraction performed to obtain the cleaned signal, $y_{\text{cleaned}}$, includes the linear and non-linear distortions of the noise signal taking place during its propagation within the medium from its source to the recording site. The adaptive gain $a^*$ applied to the template $\hat{v}_0$ deals with the amplitude variations of the real periodic perturbation signal $v_1(n)$.

3. Performance of the ESC determined with real data, recorded during pregnancy and labor

The ESC method is now tested on real ADS, recorded during pregnancy and labor, with and without medication during labor.

The first example, shown in Fig. 2a, represents the ADS recorded during pregnancy, 37 wk, from a sport woman having a no risk pregnancy. Clearly, the fECG is now the dominant component in the processed ADS (Fig. 2b).

Another example demonstrating the performance of the ESC in mECG removal from ADS is shown in Fig. 3. The ADS used here is a channel from the data set offered by De Lathauwer et al. [17], sampled at 250 Hz. Again, the mECG is mostly removed; note that the ESC is able to preserve the fECG beat even when it overlaps with the maternal T-wave.

In Fig. 4, the performance of the ESC in elaborating the fECG from ADS recorded during labor is revealed. The data depicted in Fig. 4a are recorded during labor after oxytocin administration at a sampling rate of 400 Hz. The performance of ESC is demonstrated in Fig. 4b showing a clear fECG beat train. Note that the overlapped fECG beats are extracted almost undistorted, even if the mECG shows

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**Fig. 1.** Adaptive noise canceling methods: (a) original adaptive noise canceller scheme [14]; (b) event-synchronous interference canceller (ESC) [16]. A template segment of the repetitive disturbing component is constructed from the signal channel $y(n)$ by event triggered averaging. An amplitude matched version of the template is then subtracted from the signal channel. As indicated by the switch, the extra recording of $v_1(n)$ can be substituted by using $y(n)$ instead (see Section 2).

Fig. 2. mECG removal from real ADS (normal pregnancy, 37 wk): (a) original ADS segment; (b) same segment after mECG removal by ESC. Obviously, the fECG represents now the dominant signal component. The ADS signal was preprocessed to remove the baseline wander and the power line interference. The preprocessing steps include the resampling from 1000 to 250 Hz. Ordinate scaling is arbitrary.

Fig. 3. mECG removal from real ADS (normal pregnancy): (a) original signal; (b) ESC processed ADS which preserves the fECG perfectly. Ordinate scaling is arbitrary. ADS data (sampling frequency 250 Hz) taken from De Lathauwer et al. [17].

a T-wave larger than the fetal QRS complex, and even if the baseline has fluctuations due to the uterine contractions.

Fig. 5 again shows the performance of ESC in ADS application for a recording taken during labor now without drug administration. The original ADS are depicted in Fig. 5a, whereas Fig. 5b shows it after ESC application. For details, Fig. 5c and d magnify a segment from Fig. 5a and b, respectively. Clearly, the effective removal of the mECG components can be recognized. Note that the morphology of the fECG is preserved even for the fECG segment overlapped to the mECG occurring around the abscissa value of 105.3 s. A normalized correlation factor of around 0.97 between original and processed ADS within fECG segments (example given by shaded areas in Fig. 5c,d) proves the morphology transparency of ESC, as it is also graphically demonstrated by Fig. 5e.

4. Discussions and conclusions

These examples demonstrated that the ESC cancels the mECG in the ADS very effectively, almost without distortion of the other ADS components. The ESC shows a very good extracted fECG, conserving the shape and the amplitude of the fECG recorded in the ADS due to the basic compensation concept [14]. Interestingly to note that
the ESC algorithm (basically a subtraction algorithm) is modest with respect to computational load. Certainly, there are several different problems to be solved beyond the basic ESC application in order to get a sophisticated ADS processing system suitable for fetal monitoring.

4.1. Power line rejection (PLR)

PLR represents a classical problem thus sophisticated methods are available (e.g., [18, 19]) which have to be additionally considered, since the ESC applied for mECG removal does not contribute to the PLR by itself. In principle, PLR can be implemented somewhere in the cascade between input and output but introducing it before ESC processing avoids some impact of power line interference to the mECG template construction. Also, any preprocessing must avoid distortion of the fECG; thus, again for this purpose a subtraction method like ESC should be considered.

4.2. QRS detection for template building

Indeed, ESC application should use a more sophisticated algorithm for the detection of the maternal and fetal QRS complexes to avoid unnecessary smearing of the templates. There are a lot of suggestions (e.g., [20, 21]). Certainly, using an additional standard mECG recording in addition to the abdominal channels will contribute to a more precise detection of the maternal QRS complex.

4.3. Cascaded ESC application for uterine electrohysterogram (EHG) extraction

The ADS also contain the EHG with spectral components in the frequency range of 0.1–5 Hz [22], even if the main ADS components are power line interference (PLI), mECG and fECG, with the ECGs overlapping in the frequency domain. Since they all are repetitive, basically a cascade of three ESCs each adapted to one of the components can be applied to get the EHG as the residual signal by using a sequence of PLI–ESC, mECG–ESC, and fECG–ESC. Certainly, it must be considered that the EHG does not appear in all ADS channels.

4.4. Integrating information of all ADS channels: data fusion

The selection of the best ADS channel (out of the available 12) for assessing the fECG is a more difficult problem as its representation is different between ADS channels; besides the monopolar consideration of the single channels, the differences between all possible pairs of ADS electrodes (i.e., bipolar registration) can be used as input to ESC. Thus, selection of the channel to be used represents another problem which can be simplified by checking the channels for good fECG representation by an expert. Also, this procedure must be performed from time to time again when assuming only some temporary stationarity of the ADS condition. Further, application of data fusion of all possible channels [23] which are evaluated in parallel can be considered to establish the final output signal instead of selecting one of them and discarding the others. The only restriction for this selection process is to behave finally as a linear processing to preserve the fECG morphology in ADS.

4.5. Objective performance evaluation needs a sophisticated ADS model

Finally, it should be emphasized that future development of further improved ADS evaluation procedures demands a highly sophisticated ADS model, too, which is not yet available. Only simulated ADS data based on such a model will allow quantitative performance specifications, which requires the original source signal for input–output analysis (in real data, this reference signal is not available by principle). This sophisticated ADS model will include ECG simulations for mECG and fECG, i.e., the ECG dynamic model proposed by McSharry et al. [24], as suggested in [6]. A modulation of the mECG amplitude can be also included to get more accurately models of the ADS. Work to establish such an appropriate model is ongoing.

5. Conclusion

In summary, the ESC basically proved to be a suitable ADS processor which preserves the fECG morphology for its subsequent de-
tailed analysis [1]. Certainly, fECG morphology analysis and possible contribution to clinical aspects are in the onset status, but signal processing technology necessary to perform it must be available before clinical evaluation can be achieved. The ESC algorithm is demonstrated by the mECG removal in this paper turns out to be appropriate for such a future signal processing framework for ADS evaluation. Moreover, the application of ESC is not restricted to the ADS as the electrical “reproduction” of the fetal condition, but it can be also considered for the analysis of the fetal magnetocardiographic signal [25].
Conflict of interest statement

None declared.

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