

Prenatal Telemedicine – Advances in Fetal Monitoring

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1. Introduction

Current medical research aims to continuously improve diagnostic tools, and thus to develop new assessment methods, less invasive and - when long-term monitoring is the case, as in telemonitoring systems - less annoying for the patient. Many improvements of clinical investigations are directed by cost reduction; therefore, upgrading existing inexpensive techniques such as the direct recording of biosignals from the body surface is of utmost interest (Groves, 2008).

Currently, research and development are mainly focused on offering reliable medical devices and techniques for disabled and elderly people (Alemdar et al., 2010; Feng et al. 2010; Tay, 2009; Mestre, 2005; Corchado, 2010; Fleury, 2010). Concomitantly, there are ethical and social aspects that make medical care also focus on the first years of life, including the prenatal period, since disorders and handicaps acquired during this time will be long lasting and an extreme load for the subject, for the family, and for the society, as well. Since these individuals are not autonomous, but totally dependent on the adults, the society is also responsible for their health for obvious ethical reasons. Therefore, prenatal health care is an important topic in biomedical research, and fetal monitoring is one of its most important components (Di Lieto et al., 2008; Ippolito et al., 2003; Kosa et al., 2008; Hod and Kerner, 2003; Dalfra, 2009; Kerner, 2004; Di Lieto, 2002). Fetal electrocardiogram (fECG) and electroencephalogram (fEEG) can be used to investigate the general wellbeing and the brain development.

The current clinical methods are mainly based on the fetal heart rate variability (fHRV) analysis (Kovacs et al., 2000; Varady et al., 2003; Horvath et al., 2007). Currently, the noninvasive cardiotocographic technique is the standard clinical approach because its use is possible during both pregnancy and labor. Alternatively, the fetal Doppler ultrasound is used during pregnancy, but not during labor (1) because of its sensitivity to the movement either of the mother or of the fetus, and (2) because of the errors induced by the uterine activity. Furthermore, the side effect of long-term ultrasonic exposure on the fetus and young infants is not completely clear, and that is why this method is not recommended for

hours-long monitoring. All of the above drive to the conclusion that alternative methods are necessary. Consequently, alternatives offered by other non-invasive recording techniques are extensively analyzed for fECG monitoring. Beside the fetal phonocardiographic signals (Kovacs et al., 2000), abdominal recordings are especially investigated due to the fact that the recording devices were improved significantly and simple low-cost long-term recording is allowed, considering the modern data storage technologies. Fetal monitoring through the assessment of abdominal signals (ADS) allows the screening of the fetal well-being, based on the analysis of the fetal heart rate (fHR) and of the waveform of fECG (Sato et al., 2007). The latter implies a strong advantage of this noninvasive recording method for fetal monitoring over methods such as Doppler ultrasound (Jezewski et al., 2006).

The morphology analysis of fECG is a quite important point in fetal monitoring, since the information about the fHR does not really provide all the necessary information about the development of the fetus and fetal electrocardiography (Oostendorp 1989). Rather, the analysis of the fetal P- and T-waves, the QRS complex, and the ST segments are extremely important for an accurate diagnosis of the fetus, indicating when hypoxia occurs during pregnancy. Till now, this type of information is only available during labor, through direct fetal scalp recordings. The advantage of the abdominal fECG recordings is that this information will be optionally available all the time during pregnancy and labor, as demanded by fetal telemedicine. After extracting the fECG, the relation between the fECG and mECG needs to be investigated under different conditions.

The uterine activity will also be detected and analyzed in order to investigate, how it affects the fHR knowing that the fetus has the ability to adapt to the altering conditions induced by uterine contractions translated into temporary reduction in oxygen supply and increased pressure to the fetal head. With the adequate processing techniques, the uterine activity can be investigated from the abdominal recorded signals (Diab 2007).

As the morphology of the mECG is different between ADS channels (Roche et al., 1965; Sturm et al., 2004), the methods which analyze each ADS channel independently from the others seem to be more suitable for fetal monitoring as they provide superior preservation of the fECG morphology due to the channel specific disturbance canceling. Combined with a contactless recording (Peters et al., 2007), they could be used even for long-term continuous monitoring of high risk pregnancies.

This chapter is structured as follows: Section 1 present a short introduction into the topic; Section 2 is dedicated to the information and communication strategies available in the prenatal telemedicine; the currently in use fetal monitoring techniques are described in Section 3, revealing that recording techniques appropriate for long-time fetal monitoring; Section 4 presents the methods used to extract the information about the fECG, fHR and the uterine activity from the abdominal recorded data, pointing out the contribution of the group, and reveals their performance; the last section summarizes the problems that the prenatal telemedicine could face, showing possible research directions in the field.

2. Communication networks used in the prenatal telemedicine

The solutions for long-term fetal monitoring, necessary when a high-risk pregnancy is assumed, include different levels of complexity and technological challenges, depending on the supplied information: images, videos, signals, (multimedia) electronic patient records (EPR). The lowest complexity is given when only alarm systems are implemented (Fleury et al., 2010) (e.g., birth alarm systems). This kind of systems usually provides a button that

allows to contact a call center of a medical system serving the alarm situations. The next level of complexity appears in the store-and-forward systems; here the relevant data (signals, images and processed information) are stored and forwarded for a medical examination. These systems are cheaper, due to the asynchronous transmission, and they are widely used when the real-time monitoring is not demanded (Pandian, 2007; Britt, 2006). The highest complexity is involved by real-time applications, based on the synchronous transmission. For these telemedicine systems, the use of some kind of video-conferencing equipment is common (Kyriacou et al., 2003).

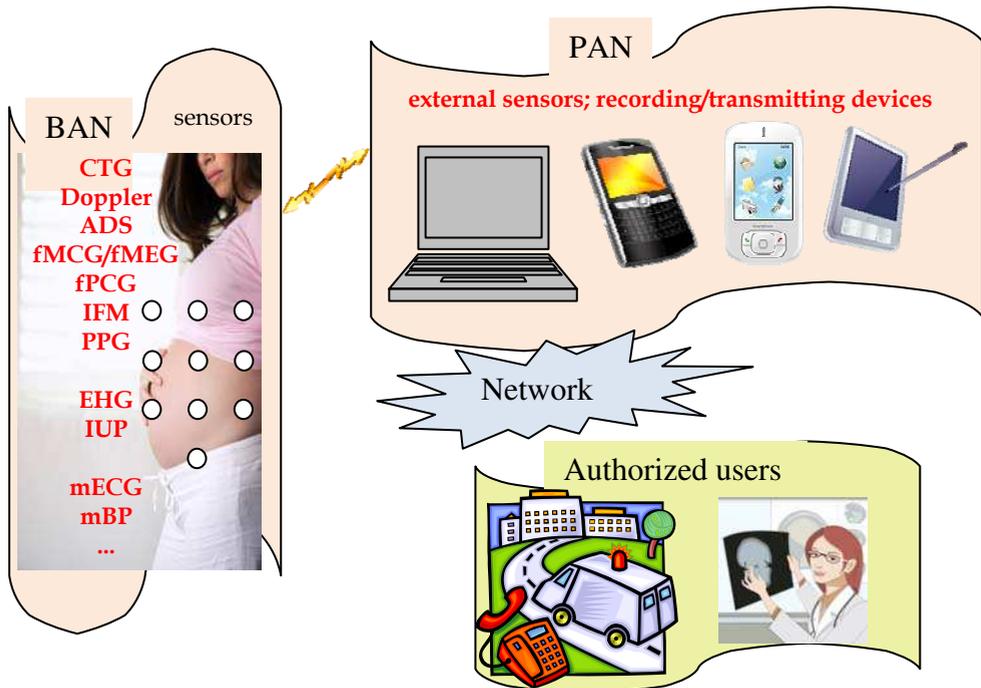


Fig. 1. A simple fetal telemedicine application scenario. Several biosignals were recorded continuously from the pregnant woman through the BAN (CTG, Doppler, ADS, fMCG/fMEG, fPCG, IFM, PPG, EHG, IUP, mECG, mBP) and monitored. They are transmitted to the PAN and further integrated into the prenatal telemedicine system to be available to authorized users.

A simple fetal prenatal application is presented in Fig. 1. The Body Area Network (BAN) (“on-body network” – OBN) consists of a group of sensors placed on the body of a pregnant woman and can be used with wireless local area network, radio (Xiao et al., 2007), Bluetooth (Omre, 2010), RFID, and Zigbee communication technique, to deliver the recorded data to the Personal Area Network (PAN).

The PAN includes (mobile) medical data acquisition devices that belong to the monitored pregnant woman (laptop, cell phone, PDA, Smartphone), and, eventually, environmental sensors spread around her (at home for example); it represents a “network of OBNs” (Alemdar et al., 2010; Dabiri et al., 2009).

The prenatal telemedicine system includes at least a base unit (doctor's unit) and a portable patient unit that communicates with each other through a wired/wireless wide area network (WAN). The traditional wired telemedicine networks, based on the Plain Old Telephony Systems (POTS) and the Integrated Services Digital Network (ISDN), and wired LAN, are lately replaced by the wireless networks (Kyriakou et al., 2003; Faddle et al., 2005) and its recently improved version, the cognitive radio approach (Feng et al., 2010; Phunchongharn & Hossain, 2010; Haykin, 2005; Matila & Maquire, 1999), using mobile phone (GPRS, GSM, G3) (Lin, 2010), or Satellite technology (Tyrer, 2009).

The communication technology for BAN, PAN, WAN is selected by considering the information transferred within/by the telemedicine system: i) CTG (cardiotocograph)/ Doppler ultrasound data, abdominal signals (ADS), fetal magnetocardiogram (fMCG), fetal magnetoencephalography (fMEG), fetal phonocardiogram (fPCG), invasive fetal monitoring (IFM - scalp electrodes), Photoplethysmography - to extract the fHR/fECG; ii) electrohysterogram (EHG), intrauterine pressure (IUP) - to analyze the uterine contractions, for labor prediction; iii) maternal ECG (mECG), maternal blood pressure (mBP), etc. - to evolution the state of the mother during pregnancy/labor.

When the medical images are of interest (e.g., Doppler ultrasound), it is necessary to implement an appropriate image communication system (Fig. 2), by designing a database for these images in such a way that the medical information can be retrieved no matter which technical method is used when the image is recorded.

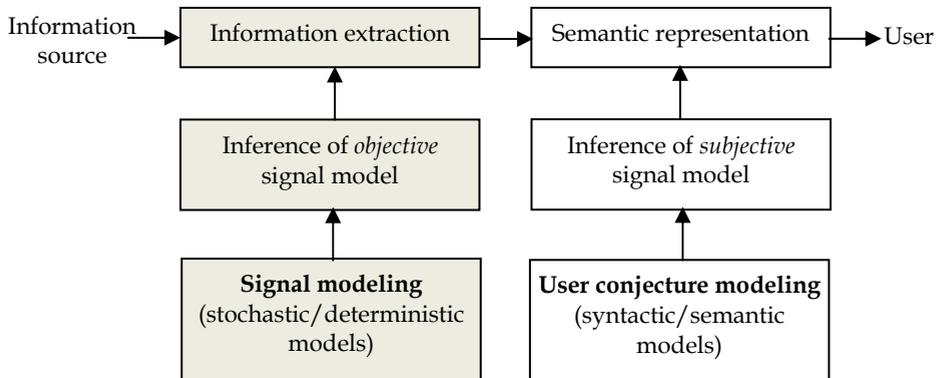


Fig. 2. Architecture of a typical image communication system

The information must be also achieved for any imaging orientation, for different body regions, considering the analyzed biological system. The challenge is then to develop tools that efficiently represent the medical images allowing physicians an easy search and comparison and a fast clinical interpretation. There is an increasing trend towards the digitization of medical images and the formation of good archives. The resulting picture archiving and communication systems (PACS) are available within a hospital allowing a global access to the shared resources. The PACS must be supplemented by a Content-Based Image Retrieval (CBIR) system so that the information the physicians are looking for is self-contained. In order to support data mining considering huge medical image databases, all approaches for CBIR systems compute a certain set of features, which are stored in the

database and linked to the original image. Regarding the integration of CBIR systems into PACS there is no need to analyze whether these features are global, local, and hierarchical or of other more complex structure. This information is integrated internally by the CBIR system. The CBIR system must have a manual interface for data entry and a mechanism for relevance feedback and query refinement (Strungaru et al., 2006). In Table 1, some of the telemedicine systems available for prenatal/pregnancy monitoring are mentioned; their transmitted signals and communication technology for BAN/PAN/network are specified.

No	Author(s)/Publication/Monitoring System	Year	Data transmitted	Transmission Communication Technology
1.	Graatsma E., Jacod B., van Egmond L., Mulder E., Visser G. (2009)/ Fetal electrocardiography: feasibility of long-term fetal heart rate recordings. <i>BJOG</i> , Vol. 116, (2009) 334–338./ Monica AN 24	2009	ADS: fHR/mHR/UA (uterine activity) data, fetal position	BAN: bluetooth PAN/network: mobile phone
2.	Kerner R., Yogev Y., Belkin A., Ben-Haroush A., Zeevi B.&Hod M. (2009)/ Maternal self-administered fetal heart rate monitoring and transmission from home in high-risk pregnancies. <i>Int. J. Gynaecol. Obstet.</i> , Vol. 84, No. 1 (Jan 2004) 33-39	2004	ADS: (fetal movements, uterine contractions)	network: telephone
3.	Kovacs F, Horvath C, Torok M, Hosszu G. (2005)/ <i>Conf Proc IEEE Eng Med Biol Soc.</i> 2005;4(1):3946-3949	2005	PCG: fHR and additional PCG data	PAN/network: mobile phone (GPRS)
4.	Di Lieto A, De Falco M, Campanile M, Török M, Gábor S, Scaramellino M, Schiraldi P, Ciociola F. (2008)/ Regional and international prenatal telemedicine network for computerized antepartum cardiotocography. <i>Telemed J E Health.</i> 2008 Jan-Feb;14(1):49-54./ TOCOMAT	2008	CTG: fHR UC	network: modem
5.	Dalfrà MG, Nicolucci A, Lapolla A; TISG. (2009)/ The effect of telemedicine on outcome and quality of life in pregnant women with diabetes. <i>J Telemed Telecare.</i> 2009;15(5):238-42.	2009	Blood glucose	

Table 1. Implemented telemedicine systems for prenatal/pregnancy monitoring

3. Available pregnancy/fetal monitoring techniques

The available fetal/pregnancy monitoring techniques as presented in Fig. 1 are all potential sources of information for a prenatal telemedicine system; they will be described in this section in some detail.

3.1 Investigation of the fetal heart

The usual investigation of the fetal heart means to analyze the fHR, i.e. the instantaneous fHR (Ungureanu et al., 2009; Bommel, 1968) or its spectrum (Cerutti et al., 1996). In addition some other statistical analyses can be performed (see the CTG section below). The recent progress in recording techniques and information technology encourage research to extend the analysis over the morphological parameters of the fECG, such as: PR-interval, PR-Segment, QRS-Interval, QT-Interval, ST-Segment, ST-Interval, QRS-Amplitude, T-Wave Amplitude, shape of the QRS, P-Wave (Taylor et al., 2003; Vrinson et al., 2004; Hayashi et al., 2009).

Doppler ultrasound

Doppler ultrasound is used to evaluate the hemodynamic components of vascular impedance and it is usually used in cases of fetal growth restriction (FGR). It is also applied to investigate the blood vessels (maternal uterine artery, fetal middle cerebral artery and the fetal ductus venosus) when evaluating the FGR (Farley & Dudley, 2009). The hypoxia related with FGR generates a brain-sparing reflex similar to that noticed in other fetal hypoxemia cases.

The parameters usually measured are: peak systolic flow velocity, the diastolic flow velocity at the end of the cardiac cycle (end-diastolic flow velocity – EDV), the systolic/diastolic ratio (S/D ratio), resistance index: $\frac{\text{peak systolic velocity} - \text{end diastolic velocity}}{\text{peak systolic velocity}}$, pulsatility

index: $\frac{\text{peak systolic velocity} - \text{end diastolic velocity}}{\text{average frequency shift over entire cycle}}$.

Cardiotocography

The ultrasound Doppler method combined with the recording of the uterine activity by applying an external pressure transducer is known as *cardiotocography* (CTG) (Signorini et al., 2003; Warrick et al., 2009). The fHR is measured and analyzed by investigating the baseline, the fHRV, the accelerations and the decelerations. In addition, the uterine pressure (UP) is used to extract the following parameters that describe the uterine activity: the contraction frequency, duration, intensity. Based on the fHR and UC the physician can recognize when the well-being state of the fetus is affected by the hypoxia.

Abdominal recordings

Abdominal recording (ADS), including the fECG, is a non-invasive method suitable for long-term fetal monitoring, and it involves the recording of the electrical signals which arise on the mother's abdomen, using surface electrodes. With the ADS it is common to monitor the fHR and the fECG, throughout pregnancy and in labor. The parameters extracted from the fECG give vital information about the fetal health status and its development. Thus, monitoring starting early in the pregnancy can observe whether the fetus is stressed, whether some critical health problems (i.e. cardiac dysfunction) could appear, or whether asphyxia appears. The method is preferred because it has no potential risk and greatly increases the comfort of the mother and the fetus. In addition, the method can be used continuously throughout pregnancy when using a belly belt of sensors.

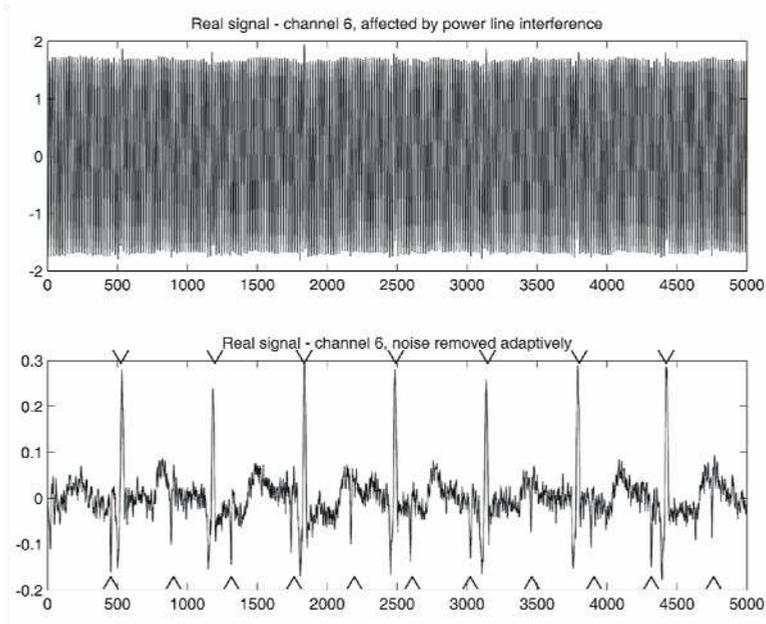


Fig. 3. Real ADS signal – channel 6, noisy (upper plot) and adaptively filtered (lower plot). fECG (∧) and mECG (∇) are indicated in the plot.

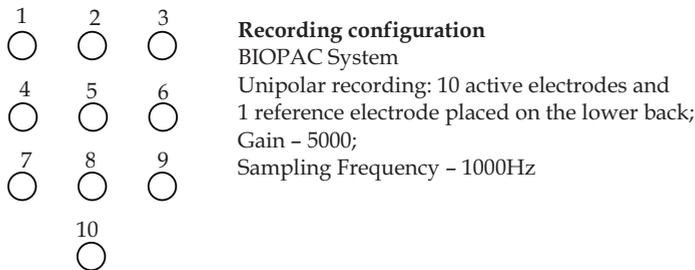


Fig. 4. Electrode placement for unipolar ADS recordings.

The fECG is not the only biosignal projected on the maternal abdomen; the disturbing biosignals are the mECG, the electromyogram (EMG) generated by maternal abdominal muscle activity, and electrohysterogram (EHG) which is the electromyogram originating from the uterine activity. In addition, the following disturbances must be considered: noise of the measurement sensors and systems, the power line interference, and the baseline wander (Matonia et al., 2005; Ungureanu et al., 2009). The main source of disturbances is the mECG. The transabdominal fECG R-peak amplitude ranges from 10 to 100 μV , while the amplitude of the maternal QRS complex shows 0.5 - 10 mV. The uterine contractions are strongly disturbing the fECG, too, especially during labor. The slow baseline wander of the signals is caused by the respiratory process and by changes of the skin-electrode-contact. All these noise sources overlap the transabdominal fECG in the time and frequency domain, and a simple high-pass filter cannot be applied to the ADS, for fECG extraction. Another

problem would be the unwanted phase distortion of the fECG, introduced by filters in signal preprocessing. The amplitude of fECG obtained through the ADS depends on the electrode configuration and varies among subjects due to the different body size of the mother and due to the position of the fetus. Considering these hard conditions, a processing of the ADS to extract the fECG is a difficult task. The ADS usually provides the fHR (or the RRI - R-R Interval), but depending on the method applied to get the information about the fetal heart, a more complex analysis that considers the fECG morphological features (waves, segments) can be applied (Ungureanu et al., 2009; Sato et al., 2007). Figure 3 shows an example of an ADS segment, obtained when using the recording setup described in Fig. 4.

Fetal magnetocardiography

The fetal heart is lately more and more investigated by using the fetal magnetocardiography (fMCG), a non-invasive method not affected by the appearance of the vernix caseosa. It provides fECG signals of a quality good enough to allow not only the instantaneous fHR monitoring but also the analysis of the fECG morphology (Comani et al., 2007; Hoyer et al., 2009; Lewis, 2003; Comani et al., 2009).

Fetal phonocardiography

The fetal phonocardiography (fPCG) represents a good alternative to the ultrasonic cardiocardiography, since it is a non-invasive recording technique suitable for long-term fHR/fHRV (tele)monitoring. Like the ADS-based fetal monitoring technique, it requires complex signal processing methods that extract the cardiac information from these noisy recordings (Ruffo et al., 2010).

Invasive (internal) fetal monitoring

The fetal cardiac activity can be detected, recorded and analyzed using the scalp fetal electrocardiogram, an invasive (internal) fetal monitoring method (IFM) that can be applied during labor; it can cause discomfort and complications for both the mother and the fetus. In addition, this recording technique can be applied only after the membrane rupture. This method is usually used for research purpose, to evaluate the noninvasive fetal monitoring techniques, due to its major shortcoming, its invasiveness, relying on a direct contact needle-like fetal scalp electrode (FSE) to obtain the fECG signal during labor (Taylor et al., 2003).

Abdominal Photoplethysmography

Zahedi and Beng proposed in 2008 an efficient algorithm to extract the fetal cardiac rate from the noisy abdominal photoplethysmographic signals (APPG) recorded from the maternal abdomen (Zahedi and Beng, 2008). Since the method analyzes the maternal and fetal blood pulsations, it does not allow the identification of the ECG waves and segments.

3.2 Investigation of the Uterine Activity

The current methods to monitor the uterine activity analyze either the mechanical uterine activity (using a tocodynamometer, i.e. CTG, or applying invasive methods that record the intrauterine pressure - IUP), or the electrical uterine activity (uterine EMG - an invasive method that is not applied on humans usually, and the electrohysterogram, recorded non-invasively from the maternal abdomen, usually filtered below 5Hz) (Devedeux et al., 1993).

Electrohysterogram

The EHG has a slow wave in the frequency range of 0.01 - 0.03 Hz, and a fast wave that can be divided in a low-frequency band (FWL), present in any contraction, and a high-frequency

band (FWH), a sign of an efficient parturition contraction (Devedeux et al., 1993). There is also a slow wave with a period equal to the contraction duration (0.01 – 0.03 Hz), usually undetectable in a standard recording. The following parameters are extracted from the EHG: i) Burst duration (D); ii) Peak-to-peak action potential amplitude (Amp); iii) frequency of bursts (F1); iv) the intrinsic spike frequency within each burst (F2). They allow to identify a normal labor (Amp > 400 μ V), to analyze the efficiency of the contractions (a high enough F2; a shift of FWL to higher frequency, indicated by the FWH power/ FWL power ratio), to predict the term and preterm labor (Maner et al., 2003; Khalil & Duchene, 2000), to detect the preterm labor or to recognize the fetus motion. A variation of the F2 within a burst is noticed when the IUP increases.

Intra-uterine pressure

The intra-uterine pressure (IUP) measured invasively is the most accurate recording technique in use for monitoring the uterine activity. Unfortunately, it cannot be applied in early pregnancy, and it is exposed to a high risk of infection or of induction of labor (Schlembach et al., 2009). The parameters measured are usually: the strength, the frequency and the duration of contractions. The values of the maximum rate of rise of pressure and the extrapolated maximum muscle velocity are also used, to make the difference between dysfunctional uterine activity and contractions specific to delivery (Devedeux et al., 1993).

4. Signal processing methods to extract the fetal ECG and the uterine activity from abdominal signals

The fundamental problem in extracting fECG from ADS is that they do not contain only the signal of interest, the fECG, but also other disturbing signals which have higher amplitudes than the fECG component and, in addition, are overlapping with it in the spectral domain. Some recent publications (Vijila et al., 2005; Guerrero-Martinez et al., 2006; Najafabadi et al., 2006; Assaleh 2007) underline that this topic currently attracts huge research efforts. Among the "noise" signals in ADS, the mECG is clearly the most salient source of disturbance, since its R-peak shows amplitudes 2 to 10 times greater than the amplitude of the fetal R-peak (Cicinelli 1994). The fECG R-peak amplitude ranges from 10 to 100 μ V (Shao et al., 2004; Bemmel 1969) in a good ADS recording where the fECG can be detected.

Other disturbing signals which must be considered are the electronic noise (introduced by amplifiers etc), the baseline wander of signals, the myoelectric crosstalk, and, in particular during labor, the uterine contractions. The latter evoke electrical activity which can be recorded by unipolar or bipolar electrodes placed on the abdomen of the mother and can be extracted by applying a bandpass filter set at 0.1 – 5 Hz to the ADS; the resulting signal is called EHG, and shows an amplitude range from 100 μ V to 500 μ V (Devedeux et al., 1993).

The large amplitude of the EHG, particularly during labor, is hiding the fECG, and a simple high-pass filtering of abdominal signals for fECG extraction cannot be applied due to the overlapping spectra of the EHG and the fECG. Also, a filter would introduce some phase distortion of the fECG. The amplitude of the fECG depends also on the electrode configuration and varies among subjects due to the different body mass index of the mother and also due to the different positions of the fetus. In addition, the fECG changes with time, especially with the appearance of the vernix in the last three months of pregnancy, when the R-peak of the fECG is hardly detectable (Bemmel 1969).

All these confounding factors reveal the need for reliable methods for removing the mECG and EHG when analyzing the fECG based on ADS recordings. Some methods have been

proposed to extract the fECG for fHR computation, such as principal component analysis (PCA), independent component analysis (ICA) (de Lathauwer et al., 2000) and nonlinear state-space projections (NSSP) (Richter et al., 1998), but the increasing interest of physicians to consider not only the instantaneous fHR but also the waveform of the fECG introduces new requirements, thus filtering methods in general are getting more demanded. For example, adaptive noise cancelling using standard mECG recordings in addition (Widrow et al., 1975) and the event-synchronous cancelling method (Ungureanu and Wolf, 2006; Ungureanu et al., 2009), as well as an adaptive maternal beat subtraction using an approximation by some previous linearly combined segments (Comani et al., 2004; Vullings et al., 2007) are applied to remove the mECG and to extract the fECG. All these methods require a template for the mECG time course within one beat cycle estimated from the recorded signal; for this purpose, first the maternal R-peaks are detected in either the ADS or the standard mECG recording by applying some pattern recognition algorithm (Friesen et al., 1990); then, the mECG template is estimated from ADS signal segments around the detected R-peaks. Most of the methods apply some preprocessing steps to remove the baseline wander, the power line interference and the mECG (Taylor et al., 2003; Martens et al., 2007), indicating again the importance of providing valuable methods for noise removing and fECG extraction. An additional standard mECG recording in addition to the abdominal channels will contribute to a more precise detection of the mQRS complex.

The analysis of the uterine contractions provides useful information about the development of the pregnancy and parturition. The most important point in the uterine activity analysis is to predict the pre-term delivery, as the premature birth is the leading cause (85%) of infant death and the source of neurological, mental, behavioral and pulmonary problems in later life (Garfield et al., 2005). Nowadays, the only method to absolutely detect pre-term labor is the permanent contact and care from physicians (Maner et al., 2003) in a hospital, which represents an expensive solution. An alternative to early detect pre-term labor by an effective automatic procedure for uterine activity monitoring (home care solution within a prenatal telemedicine system) is not yet available. Some attempts to accurately detect the preterm labor involve the invasive recording of uterine activity (Shi et al., 2008; Jiang et al., 2007).

4.1 Event Synchronous Interference Canceller

Event Synchronous Interference Canceller (ESC) removes a repetitive disturbing signal available from an additional recording channel n from the recorded signal y in order to extract the signal of interest. A 'Compensation' block performs the gain adaptation that considers the intersegment variation for the repetitive disturbing signal. The additional recording of the noise signal is not necessary when the disturbance has an amplitude strong enough to allow the detection of the repetitive segments, as is the case of fECG extraction from abdominal signals. However, the recording of the additional standard mECG improves the extraction and the analysis of the resulting fECG. ESC simply subtracts an artificial repetitive reference (which represents an approximation of the disturbing signal) from the input signal, for denoising. The artificial reference signal is determined by repeating the template disturbing segment, obtained by averaging the noise segments contained in the recorded disturbed signal y (Ungureanu & Wolf, 2006).

The subtraction performed to obtain the cleaned signal, includes the linear and non-linear distortions of the noise signal associated with the signal path and the recording techniques. The adaptive gain a' applied to the averaged template includes the amplitude variations in the real periodic noise signals and is obtained as the value which minimizes an error

function over $[a_1; a_2]$. In order to avoid the instability, the interval of minimization is chosen to be $[0.9, 1.1]$. An example of fECG extraction from ADS signals is shown in Fig. 5.

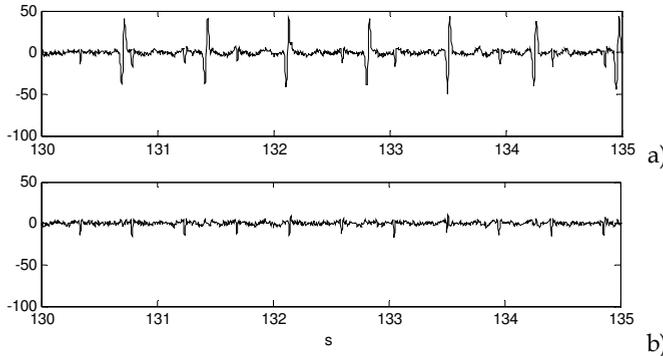


Fig. 5. Results obtained when applying the ESC for fECG extraction from a real ADS signal, recorded at 1000 Hz. a) ADS signal; b) fECG extrated by the ESC algorithm.

4.2 Principal component analysis

PCA procedure reduces the number of uncertainties and identifies the major components based on the fact that they have the most significant variance. Let us consider that we have N samples for each channel, x_i , and that the data vector is D -dimensional: $\mathbf{x} \in \mathbf{R}^D$. PCA replaces these vectors by lower-dimensional vectors with dimension C , where $C < D$. Considering the linear transformation for these vectors, we obtain:

$$\mathbf{x} = \mathbf{W}\mathbf{s} + \mathbf{b} = \sum_{j=1}^C \mathbf{w}_j s_j + \mathbf{b} \tag{1}$$

where the matrix \mathbf{W} is described by $\mathbf{W} = [w_1 \ w_2 \ \dots \ w_C]$.

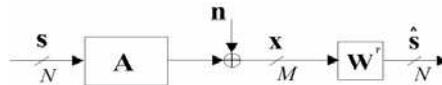


Fig. 6. PCA method - Data decorrelation

This corresponds to a real case where we have a set $\{x_i(k)\}$ of measurements, each with N samples ($k = 1, 2, \dots, N$), and from it we want to extract the set $\{s_i(k)\}$ for a further analysis; \mathbf{b} is the average component. There are two different approaches to compute the matrix \mathbf{W} , namely the eigenvector method (EVD) and singular value method (SVD). The algorithms are the following:

PCA (EVD)

1. Let $\mathbf{b} = \frac{1}{n} \sum_i x_i$ be the mean vector.

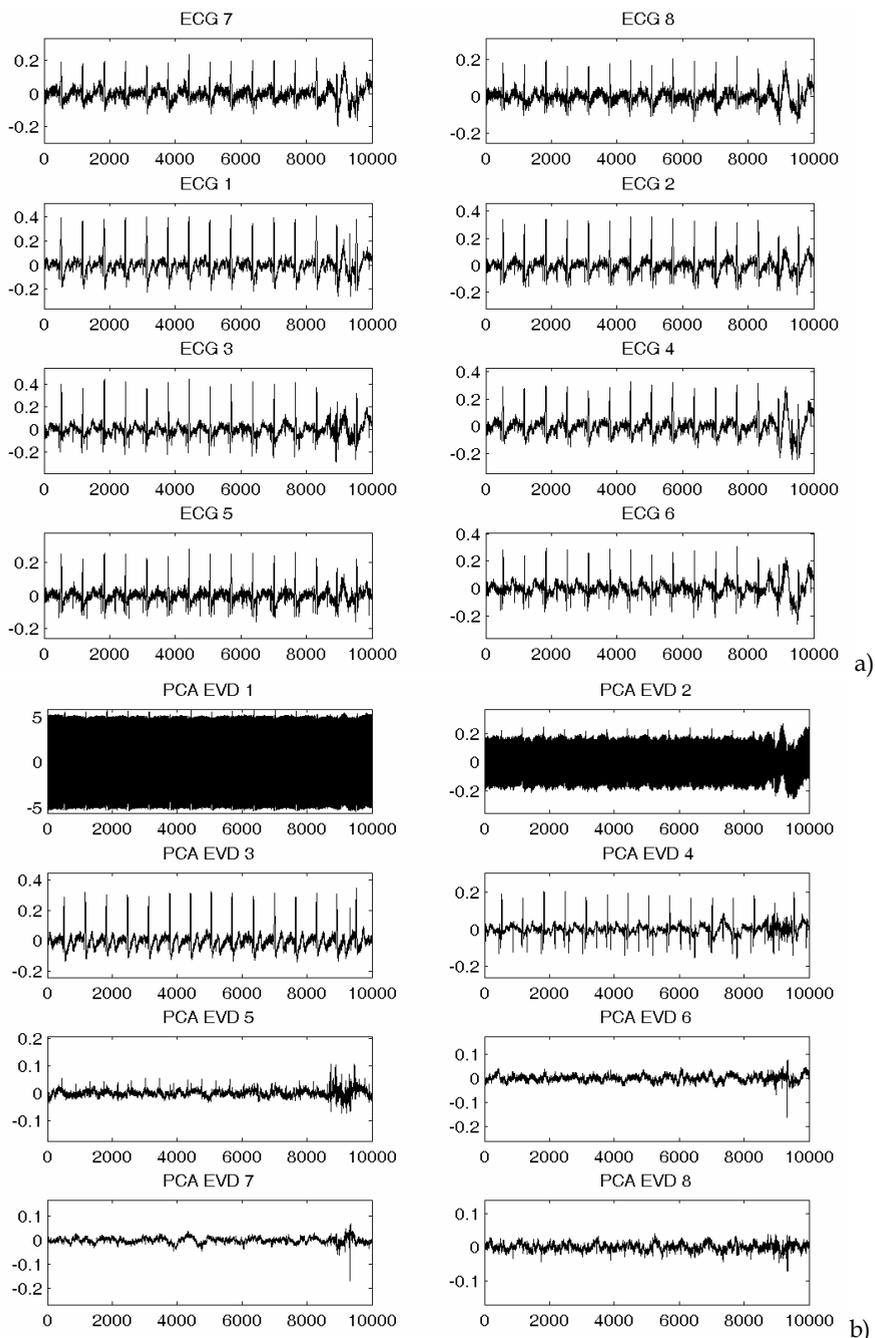


Fig. 7. Results obtained when applying the PCA-EVD method to ADS signals, to extract the fECG. Note that the fECG is not extracted properly. a) real signals; b) extracted components.

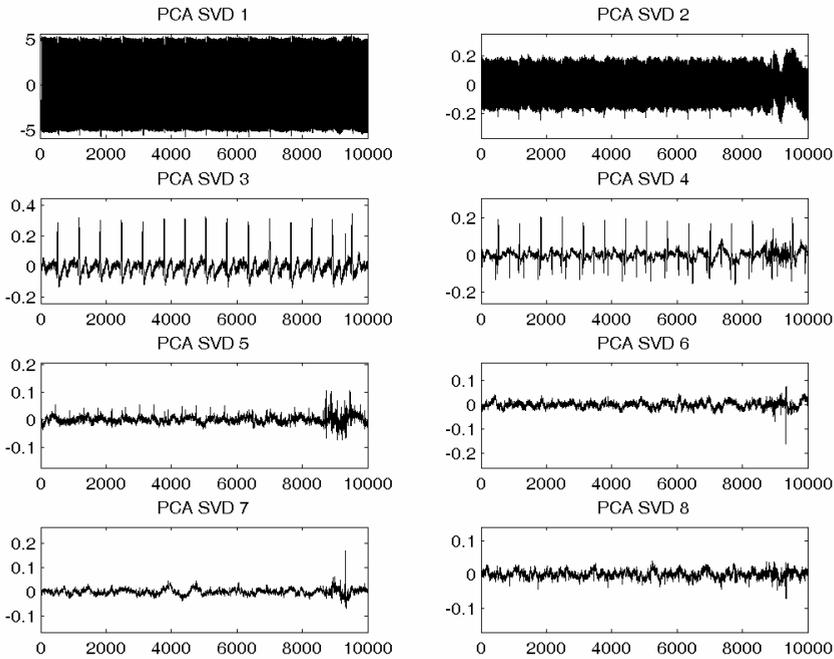


Fig. 8. Results obtained when applying the PCA-SVD method (the real signals are shown in Fig. 7.a). Note that the fECG is not extracted well.

2. Let $\mathbf{K} = \frac{1}{n} \sum_i (x_i - \mathbf{b})(x_i - \mathbf{b})^T$ be the covariance matrix.
3. Let $\mathbf{V}\mathbf{\Lambda}\mathbf{V}^T = \mathbf{K}$ be the eigenvector decomposition of \mathbf{K} . $\mathbf{\Lambda}$ is a diagonal matrix of eigenvalues \mathbf{K} ($\mathbf{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_D)$). The matrix \mathbf{V} contains the eigenvectors: $\mathbf{V} = [\mathbf{v}_1, \dots, \mathbf{v}_D]$ and is orthonormal $\mathbf{V}^T\mathbf{V} = \mathbf{I}$.
4. Let us assume that the eigenvalues are sorted from the largest to the smallest one ($\lambda_i \geq \lambda_{i+1}$). If this is not the case, then we firstly sort them (and their corresponding eigenvectors).
5. Let us consider the estimated noise variance: $\sigma^2 = \frac{1}{D-C} \sum_{j=C+1}^D \lambda_j$ (it is equal to the average marginal data variance over all the directions that are orthogonal to the C principal directions; i.e., this is the average variance per dimension of the data that is lost in the approximation of the data in the C dimensional subspace).
6. Let $\tilde{\mathbf{V}}$ be the matrix comprising the first C eigenvectors: $\tilde{\mathbf{V}} = [\mathbf{v}_1, \dots, \mathbf{v}_C]$, and let $\tilde{\mathbf{\Lambda}}$ be the diagonal matrix with the C leading eigenvalues: $\tilde{\mathbf{\Lambda}} = [\lambda_1, \dots, \lambda_C]$.
7. Compute $\mathbf{W} = \tilde{\mathbf{V}}(\tilde{\mathbf{\Lambda}} - \sigma^2\mathbf{I})^{\frac{1}{2}}$.
8. Compute $\mathbf{s}_i = \mathbf{W}^T(x_i - \mathbf{b})$, for all i .

PCA (SVD)

1. Let $\mathbf{b} = \frac{1}{n} \sum_i x_i$ be the mean vector \mathbf{x} . Translate the origin to the center of gravity, *data center*.
2. Calculate the singular centered values of data, $\tilde{\mathbf{X}} = \mathbf{U}\Sigma\mathbf{V}^T$.
3. Compute the variances by squaring the singular values. Since $\sum_i (x_i - \mathbf{b})(x_i - \mathbf{b})^T = \mathbf{U}\Sigma\mathbf{V}^T\mathbf{V}\Sigma\mathbf{U}^T = \mathbf{U}\Sigma^2\mathbf{U}^T$ and considering that $\mathbf{V}\Lambda\mathbf{V}^T = \mathbf{K}$, \mathbf{U} contains the eigenvector of \mathbf{X} . The diagonal values in matrix Σ are the *singular values* (the square roots of the *eigenvalues* of $\mathbf{X}\mathbf{X}^T$).
4. Compute $\mathbf{s}_i = \mathbf{U}^T(\mathbf{x}_i - \mathbf{b})$, for all i .

4.3 Independent component analysis

ICA extracts the components that are not only decorrelated but also independent. It considers the computation of higher order moments (3rd and 4th moment) and is suitable for signals that have no more than one Gaussian component. The algorithm is briefly described in the figure below:

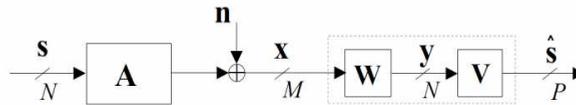


Fig. 9. ICA model - BSS extraction of P signals

ICA extracts the signal sources by applying the matrix inverse:

$$\mathbf{s} = \mathbf{A}^{-1}\mathbf{x} \tag{2}$$

Two of the most representative ICA algorithms reported in the literature are: i) JADE (joint approximate diagonalization of eigen-matrices) developed by J. F. Cardoso and Antoine Souloumiac (1993), and ii) Fast-ICA, developed by Hyvärinen (1999); it is based on a fixed-point iteration scheme maximizing non-Gaussianity as a measure of statistical independence. The idea of ICA is to extract the vector sources, \mathbf{s} , with q components, from the recorded vector \mathbf{x} , including p channels:

$$\mathbf{x} = \mathbf{A}\mathbf{s} + \mathbf{n} \tag{3}$$

\mathbf{A} is the mixing matrix, \mathbf{n} represents the additive noise. The following assumptions must be met in order to apply ICA:

1. \mathbf{A} has linear independent columns (satisfied for real signals usually)
2. \mathbf{x} contains independent variables
3. \mathbf{n} and \mathbf{x} are independent.

Under these assumptions the mixing matrix can be estimated and the sources are extracted:

$$\mathbf{s} \approx \hat{\mathbf{s}} = \hat{\mathbf{A}}^{-1}\mathbf{x} \tag{4}$$

ICA (JADE)

It is the most applied ICA algorithm and uses the fourth-order cumulants to compute the kurtosis. The steps of the algorithm are:

1. Initialization (data whitening):

$$\hat{\mathbf{W}} = \text{diag}\left(\left(\lambda_1 - \hat{\sigma}^2\right)^{-1/2}, \dots, \left(\lambda_q - \hat{\sigma}^2\right)^{-1/2}, 0, \dots, 0\right) \mathbf{V}^T,$$

with $\hat{\mathbf{y}} = \hat{\mathbf{W}}\mathbf{x}$ and,

$$\hat{\sigma}^2 = \frac{1}{p-q} \cdot \sum_{j=p+1}^q \lambda_j,$$

with $q < p$.

2. Computation of the Kurtosis for $\hat{\mathbf{y}}$; the set of the fourth-order cumulants, $\{Q_i^y\}$, is obtained.
3. Optimize an orthogonal contrast: the matrix \mathbf{V} has to be estimated so that the contrast function is minimized:

$$\varphi^{JADE} = \sum_{ijkl \neq iikl} Q_{ijkl}^y = \sum_i \text{off}\left(\mathbf{V}^T \mathbf{Q}_i^y \mathbf{V}\right)$$

where $\text{off}(\mathbf{A})$ are the nondiagonal elements:

$$\text{off}(\mathbf{A}) = \sum_{i \neq j} a_{ij}$$

The matrix \mathbf{V} is computed using the Jacobian.

4. Mixing matrix estimation:

$$\hat{\mathbf{A}} = \mathbf{W}^T \mathbf{V}$$

5. The extraction of the independent components:

$$\mathbf{s} \approx \hat{\mathbf{s}} = \mathbf{V}^T \mathbf{y} = \mathbf{V}^T \mathbf{W} \mathbf{x}$$

ICA (FastICA)

The FastICA (a fast, batch type algorithm for performing ICA) learning rule finds a direction, i.e. a unit vector \mathbf{w} , such that the projection $\mathbf{w}^T \mathbf{x}$ maximizes the nongaussianity. Nongaussianity is here measured by the approximation of negentropy $J(\mathbf{w}^T \mathbf{x})$. Recall that the variance of $\mathbf{w}^T \mathbf{x}$ must be here constrained to unity; for whitened data this is equivalent to constraining the norm of \mathbf{w} to be unity. The FastICA is based on a fixed-point iteration scheme for finding a maximum of the nongaussianity of $\mathbf{w}^T \mathbf{x}$. It can be also derived as an approximative Newton iteration [9]. Let us denote by g the derivative of the nonquadratic function G used in definition of negentropy. The following choices of G have been proved very useful: $G_1(u) = 1/a_1 \log \cosh(a_1 u)$ or $G_2(u) = -\exp(-u^2/2)$; the derivatives of G functions are $g_1(u) = \tanh(a_1 u)$, and $g_2(u) = u \exp(-u^2/2)$, where $1 \leq a_1 \leq 2$ (usually $a_1 = 1$).

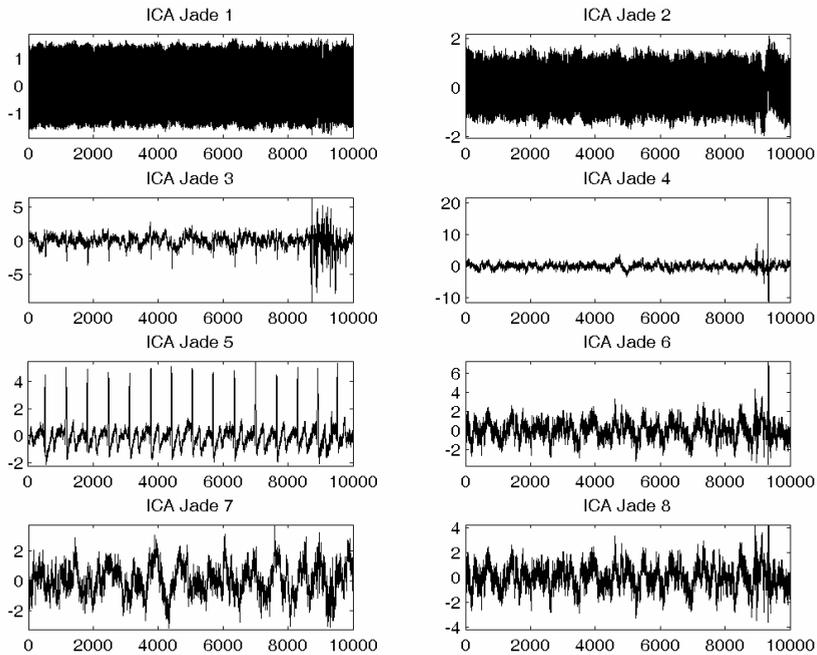


Fig. 10. Results obtained when applying the ICA-JADE method (the real signals are shown in Fig. 7.a). Note that the fECG is not visible in the extracted components.

The steps of the algorithm are:

1. *Data whitening*; the whitened matrix is estimated by:

$$\hat{\mathbf{W}} = \text{diag} \left((\lambda_1 - \hat{\sigma}^2)^{-1/2}, \dots, (\lambda_q - \hat{\sigma}^2)^{-1/2}, 0, \dots, 0 \right) \mathbf{V}^T,$$

where $\hat{\mathbf{y}} = \hat{\mathbf{W}}\mathbf{x}$, and

$$\hat{\sigma}^2 = \frac{1}{p-q} \sum_{j=p+1}^q \lambda_j$$

with $q < p$. Whitening is always accomplished by principal component analysis.

2. Choose an initial (e.g. random) weight vector \mathbf{w} .
3. Let $\mathbf{w}^+ = E\{\mathbf{x}g(\mathbf{w}^T\mathbf{x})\} - E\{g'(\mathbf{w}^T\mathbf{x})\}\mathbf{w}$
4. Let $\mathbf{w} = \frac{\mathbf{w}^+}{\|\mathbf{w}^+\|}$.
5. If not converged, go back to step 3.

The one-unit algorithm described above (a "unit" refers to a computational unit, eventually an artificial neuron, having a weight vector \mathbf{w} that the neuron is able to update by a learning

rule) can be extended, to obtain the whole ICA transformation, $\mathbf{s} = \mathbf{W}^T \mathbf{x}$. To prevent different neurons from converging to the same maxima, the outputs $\mathbf{w}_1^T \mathbf{x}, \dots, \mathbf{w}_n^T \mathbf{x}$ are decorrelated after every iteration. A simple way to accomplish this is a deflation scheme based on a Gram-Schmidt-like decorrelation: whenever p independent components are estimated (p vectors $\mathbf{w}_1, \dots, \mathbf{w}_p$), the one-unit fixed-point algorithm for \mathbf{w}_{p+1} is applied, and after each iteration step the projections of the previously estimated p vectors are subtracted from \mathbf{w}_{p+1} ; \mathbf{w}_{p+1} is then renormalized:

$$\mathbf{w}_{p+1} = \mathbf{w}_{p+1} - \sum_{j=1}^p \mathbf{w}_j \mathbf{w}_j^T \mathbf{w}_{p+1}, \quad \mathbf{w}_{p+1} = \frac{\mathbf{w}_{p+1}}{\|\mathbf{w}_{p+1}\|}$$

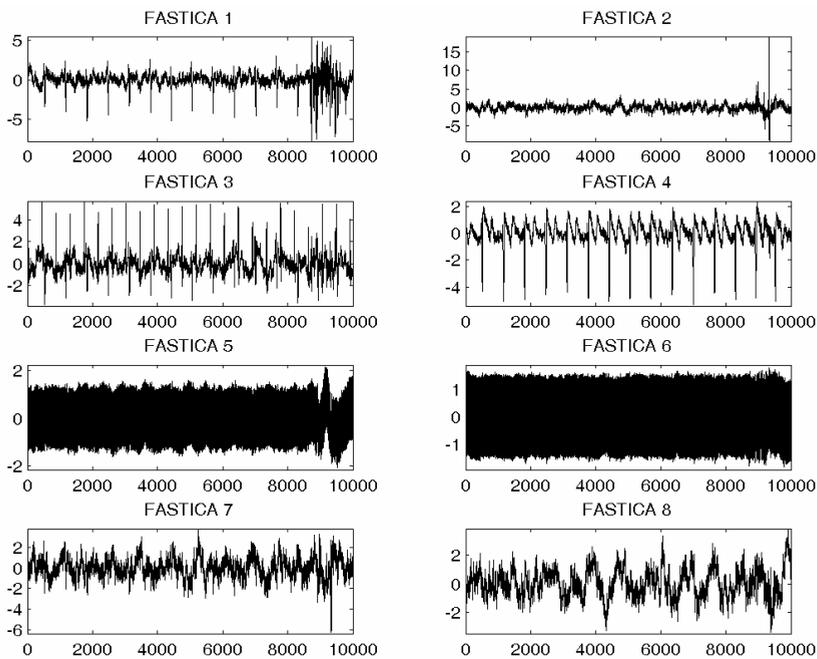


Fig. 11. Results obtained when applying the ICA-FastICA method (the real signals are shown in Fig. 6.a). Note the clear extracted fECG in the 2nd ICA component.

The above decorrelation scheme is suitable for the separation of the independent components. Sometimes it is more convenient to estimate all the independent components simultaneously, and use a symmetric decorrelation. This can be accomplished by the following transformation:

$$\mathbf{W} = \mathbf{W}(\mathbf{W}^T \mathbf{W})^{-1/2}$$

where $\mathbf{W} = (\mathbf{w}_1, \dots, \mathbf{w}_n)$.

5. Discussions and conclusions

The recent evolution in the sensors development, communications and information technology yields a lot of challenges for the researchers interested in contributing to low cost, long-term, fetal (tele)monitoring. A lot of recording techniques and signal processing methods are available, and the communication strategy offers also a lot of options, making the development of telemedicine systems a bit difficult. Among the fetal extraction methods, the event synchronous canceller method proves to be a useful tool, preserving the morphology of the fetal ECG. In addition the extraction of fECG and EHG from abdominal recordings can be enhanced by ESC application and data fusion of multichannel recordings.

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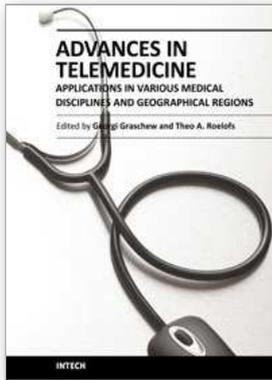
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