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Chapter 43
Acquisition and processing of the antepartum FECG

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Introduction

The fetal heart rate (FHR) and its beat-to-beat variability are important parameters in the observation of the fetal condition [17,24]. Current methods to monitor the fetal heart rate are based on a Doppler-shifted ultrasonic heart echo (ultrasound techniques) and on audio techniques (phonocardiography).

The fetal electrocardiogram (FECG) provides not only more accurate information about the fetal heart rate, but also more general information about the fetal condition. By only observing the FHR, arrhythmia and changes of the fetal heart rate can be detected. But the cardiac waveform also contains important diagnostic information. The duration of the QRS-complex e.g. is a measure to discriminate between supraventricular (a normal narrow QRS-complex) or ventricular (a wide QRS-complex) tachycardia (FHR $\geq$ 200 bpm). The position and the sign of the P-wave in the ECG waveform is very important to discriminate between the various forms of supraventricular tachycardia.

Most accurate methods to record a fetal ECG are invasive, as they use an electrode placed on the fetal scalp, and are therefore only feasible during delivery. In order to register the fetal ECG during pregnancy, non-invasive techniques must be looked for. However, it is very difficult to obtain clear, abdominally recorded, fetal heart signals from which diagnostic parameters could be derived. Indeed, when measuring the antepartum FECG from electrodes on the mother's skin, the much stronger maternal electrocardiogram (MECG) forms the largest source of interference. Furthermore, other noise sources become relatively important in comparison with the low voltage range of the FECG : the maternal EMG-activity or 'muscle noise', the noise from the electrode-skin contact and the 50 Hz net interference can disturb the observation of the FECG significantly.

During the last ten years a very promising signal separation method has been developed, that eliminates the maternal ECG from the recorded signals, such that an antepartum fetal ECG can be obtained. The method is based on the Singular Value Decomposition (SVD) of the matrix, composed from the recorded signals and has been extensively described [5,13,28,31]. In this paper we will present a number of problems we experienced with this method, when applying it to some datasets that were obtained from 12 patients. Some general conclusions that can be derived are stated. It seems that the positioning of the electrodes and the choice of the electrode pairs for signal recording are still the most crucial factors for the success of the method. Furthermore a reference is made to more recent work to determine the fetal heart rate from the fetal signals, obtained after suppression of the maternal ECG in the recordings. These methods are so robust

that, even if the quality of the signal separation is not optimal, a reliable fetal heart rate is found. At this moment the SVD-based signal separation method is implemented in a PC-based monitoring system, such that the antepartum fetal ECG - and also the fetal heart rate - can be obtained in real-time.

Elimination of the MECG

The main interference, occurring when measuring the antepartum FECG from electrodes on the mother's skin, is formed by the much stronger omnipresent maternal electrocardiogram (MECG). It is therefore evident that much attention has been put in trying to eliminate the MECG from the recorded signals before further analysis of the fetal ECG. The earliest attempts and most straightforward approaches have involved a direct scaled subtraction of a thoracic or near-thoracic MECG from an abdominally measured composite of maternal and fetal heart signals [14,19,26,27,32]. More complex methods contained averaging techniques, matched filters, auto- and cross correlation and adaptive noise cancellation [3,15,33]. Another class of methods tries to obtain a 'clean' FECG by a linear combination or weighted sum of a number of electrode signals, which is a so called spatial filtering [4,22,23,28,29]. Most of the published methods have, to our knowledge, one of the following major drawbacks : 1) When attempting to eliminate the MECG, important contributions from the FECG are often eliminated too; 2) The fetal heart activity is described by only one signal, while similar to the adult ECG it is expected that an adequate description requires more signals; 3) The FECG-to-noise ratio in the result is never better than in the original abdominal recording; 4) The application in a clinical environment is too sensitive to actual electrode location, human interaction, stage of pregnancy, position of the fetus, etc.; 5) Only certain intervals (QRS-complex) are considered to contain useful information.

An adaptive signal separation method for the extraction of the Fetal ECG from signals, recorded with electrodes on the mother's skin, has been presented [5,6,8,12]. Instead of eliminating the MECG completely from the recordings, the method suppresses the MECG substantially, resulting in a signal that mainly contains fetal heart contributions. This method is based on the Singular Value Decomposition (SVD) of a matrix [6,18] and updates the coefficients in the linear combinations of the recorded signals using an on-line scheme. The mathematical basics of this method have been described [7,9,13,30,31]. Compared with other existing techniques, the on-line SVD-based method has several advantages and benefits : several signals are processed simultaneously, such that not only the maternal ECG is suppressed, but often a signal is obtained with better FECG-to-noise ratio than in any of the recorded signals. Furthermore, this method offers the possibility to describe the fetal heart activity by more than one signal. Crucial for the success of the method is the choice of the electrode positions on the skin of the mother. In all our tests up till now, we only obtained good results with bipolar electrode signals (no reference electrode). Furthermore, in addition to one or more signals recorded from electrode pairs on the maternal abdomen, at least three signals are required from thoracic or peripheral electrode pairs, containing only contributions from the maternal ECG. In this way the problems of MECG elimination and of optimal FECG detection are decoupled.

Evaluation of MECG suppression

Several tests and experiments were performed for the evaluation of the method to obtain

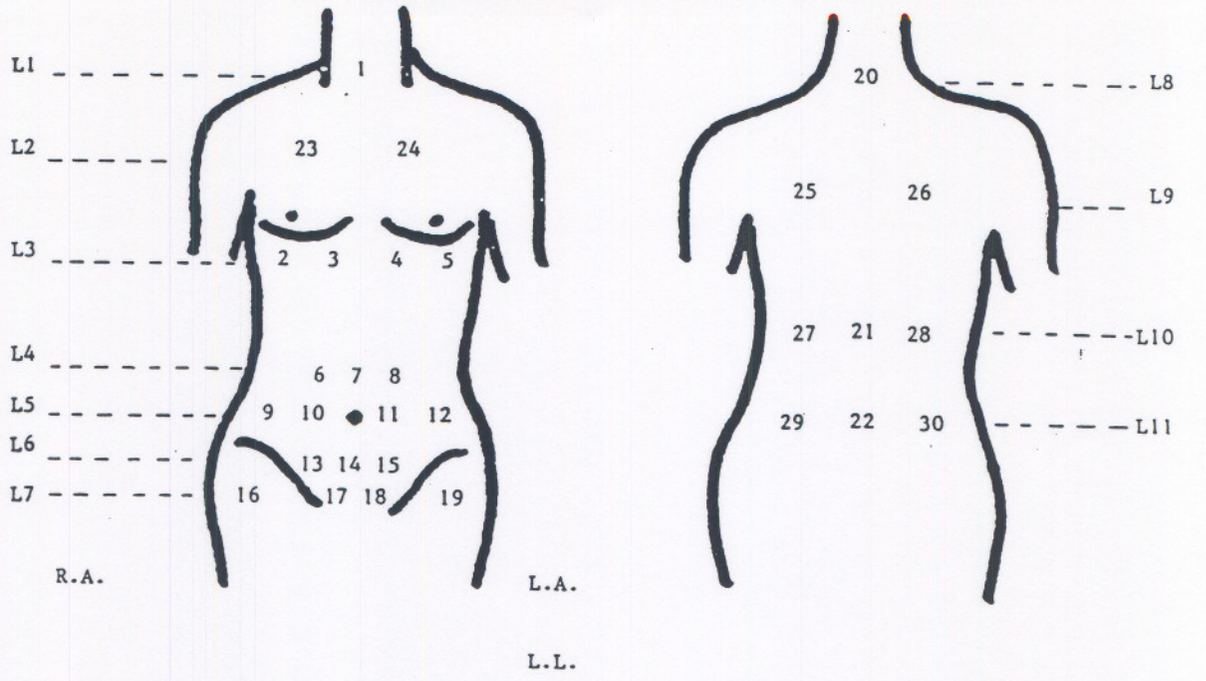


Fig 1 General configuration of 32 electrode positions, used for the recording sessions.

the antepartum fetal ECG after suppression of the maternal ECG from the signals, recorded on the abdomen of the mother. A general configuration with 32 electrode positions was defined (Figure 1) and a total of 12 female subjects were recorded, which resulted in 14 useful datasets. Per subject 7 or 8 signals were recorded simultaneously (3 thoracic and 4 or 5 abdominal) from pairs of disposable Ag/AgCl electrodes (Red Dot, 3M). These were then passed through a highpass filter (1st order) with t 0 10 or 50 ms, and a low-pass filter (2nd order) with f0=70 Hz. Furthermore, the signals were sampled at 500 Hz, digitized with 12 bit resolution, and finally stored on digital tape.

The electrode pairs were chosen according to the following strategy : 1) choose electrode locations on the maternal abdomen such that a good FECG signal-to-noise ratio is obtained, as if no maternal ECG were present; 2) choose electrode positions far from the abdomen (e.g. on the thorax, on the arms) such that the maternal ECG is recorded independently and as strongly as possible. Our experience shows that at least three independent signals, with MECG only, have to be recorded, in addition to one or more abdominal signal(s). Indeed, the electrical activity of the heart is - at a considerable distance from the heart - similar to that of a dipole, rotating in three dimensions [25]. Care must therefore be taken not to put the electrodes too close to the maternal heart, because in that case the 'rotating dipole' hypothesis no longer holds.

In general, the following conclusions can be drawn from the analysis of the recorded datasets :

1. A dataset can be called successful, if one or more abdominal signals are obtained in which the fetal QRS-complexes are more than 10 dB stronger than the noise level. We experienced that no clear - MECG free - antepartum FECG could be obtained, if the contributions from fetal heart are not sufficiently strong present in the abdominal recordings. E.g. the dataset analysed in Table 1 has three abdominal signals for which this condition is satisfactory, and will give very satisfying results.

Table 1 Maternal ECG to Fetal ECG ratios and Signal-to-noise ratios for five recorded abdominal signals

	Measured abdominal signals		
Signal Number	MECG/FECG	MECG/noise	FECG/noise
1	27.8	48.0	32.4
2	15.5	42.6	14.8
3	24.9	42.6	17.7
4	25.6	38.5	12.9
5	34.4	42.7	8.3

2. The more abdominal signals are used in the method, the less sensitive the method is from the particular choice of the electrode pairs. Table 2 shows the results obtained when only one abdominal signal is used in the signal separation method, as well as the results of all possible combinations of two, three, four and five abdominal signals. It is seen from this table that a satisfying result is obtained with three or more abdominal signals, although better FECG-to-MECG ratios can sometimes be obtained with only two signals.
3. Adding an extra (simultaneously recorded) abdominal signal will not always result in a better FEGG-to-MECG ratio. Figure 2a shows the result of the method using two simultaneously recorded abdominal signals (3+5) and three thoracic signals. In Figure 2b the result is shown if one additional abdominal signal (1+3+5), containing FECG, is used.
4. The electrical activity of the adult heart can be described by three independent signals. A similar situation may be expected for the description of the electrical activity of the fetal heart. However, in this particular case the configuration of the maternal body as a volume conductor, as well as the existence of vernix caseosa surrounding the fetus, play an important role [20]. The 'dimension' of the fetal heart, i.e. the number of independent signals describing its electrical activity, changes during the period of pregnancy [21]. By recording several abdominal signals simultaneously, it becomes possible to obtain more than one fetal ECG-signal in which the maternal ECG has been suppressed substantially. Figure 3 shows two independent fetal signals obtained from a dataset by using five abdominal signals.

The electrode positioning and the choice of the optimal electrode pairs is crucial for the success of the SVD-based signal separation method. This problem can be circumvented in two ways : the first possibility is to record as many abdominal signals as possible and to let the computer decide which of these signals will effectively be used for the signal separation method. This requires that the patient will be covered all over with electrodes and electrical wires, which is not so practical. Another solution requires a device or method to detect in first order approximation good locations for electrode positioning. Afterwards, a minimum of electrodes is used to actually obtain the antepartum FECG. At this moment no elegant and reliable method exists to select the optimal electrode positions. By implementing the SVD-based signal separation method in a PC-based bedside unit, it will become possible to evaluate a chosen electrode pair in real-time.

Table 2 FECG-to-MECG and FECG-to-noise ratios for one or more signals, obtained by applying the SVD-based signal separation method to a set of one or more abdominal signals (the combinations are indicated in this table), extended with 3 thoracic signals.

Abdominal Signal(s) Used	FECG/MECG	FECG/noise
1	9.7	26.7786
2	-.26	19.2
3	6.4	20.8
4	-	-
5	-5.9	11.4
1+2	3.9	25.5
1+3	7.2	20.2
	8.0	27.6
1+4	8.8	25.6
1+5	11.1	21.0
2+3	7.4	21.8
2+4	13.1	26.5
2+5	9.6	27.6
3+4	5.2	20.3
3+5	23.1	30.8
4+5	-	-
1+2+3	3.8	25.6
	13.6	27.7
1+2+4	6.6	20.0
1+2+5	13.6	25.0
	7.1	21.2
1+3+4	6.6	19.7
	7.7	27.4
1+3+5	3.0	26.4
	6.5	21.9
1+4+5	9.9	20.8
2+3+4	14.2	22.9
	9.9	25.2
2+3+5	6.9	26.0
	16.6	26.4
3+4+5	7.7	17.7
	22.0	29.5
1+2+3+4	16.3	24.9
	12.9	26.2
1+2+3+5	15.5	28.0
1+3+4+5	11.4	31.6
	4.6	19.6
2+3+4+5	14.3	34.4
1+2+3+4+5	17.5	25.8
	13.9	26.9

Fetal heart rate determination

Figure 3a shows a typical signal, containing the antepartum fetal ECG, obtained after suppression of the maternal ECG from abdominal recordings by using the SVD-based signal separation method. In this section we will describe a method to determine the fetal

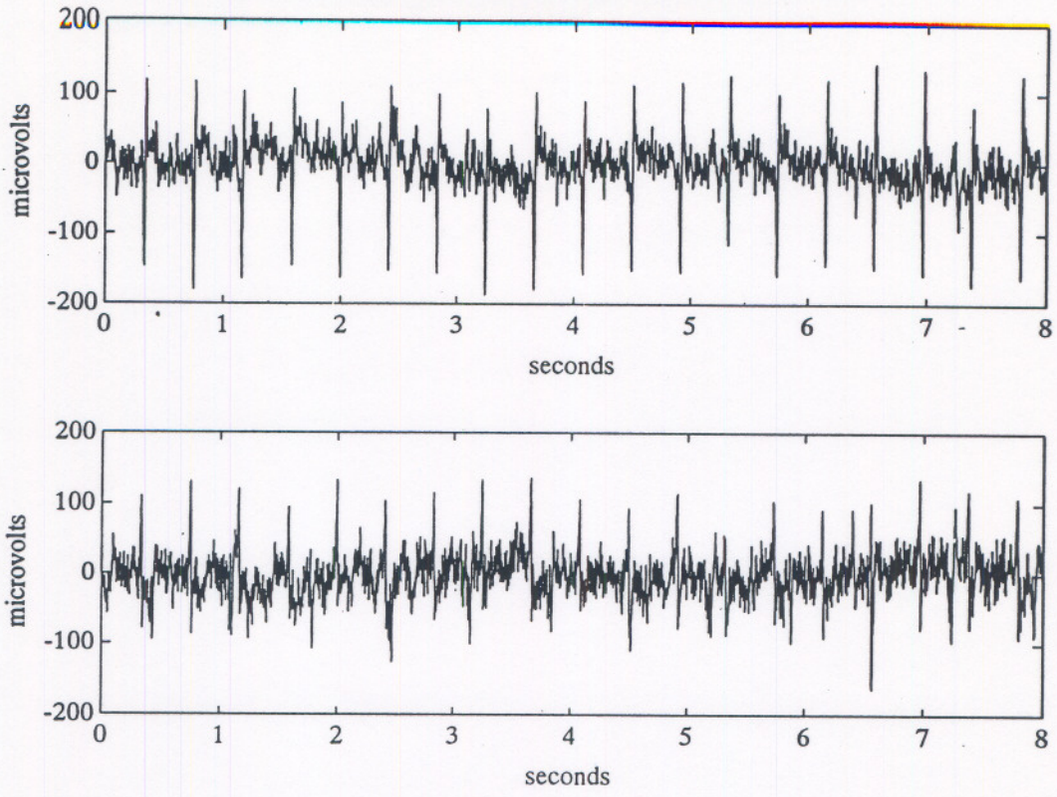


Fig 2 Two signals resulting from the signal separation method : a) Signal resulting when only two abdominal signals (3+5) are used; b) Signal resulting when three abdominal signals (1+3+5) are used.

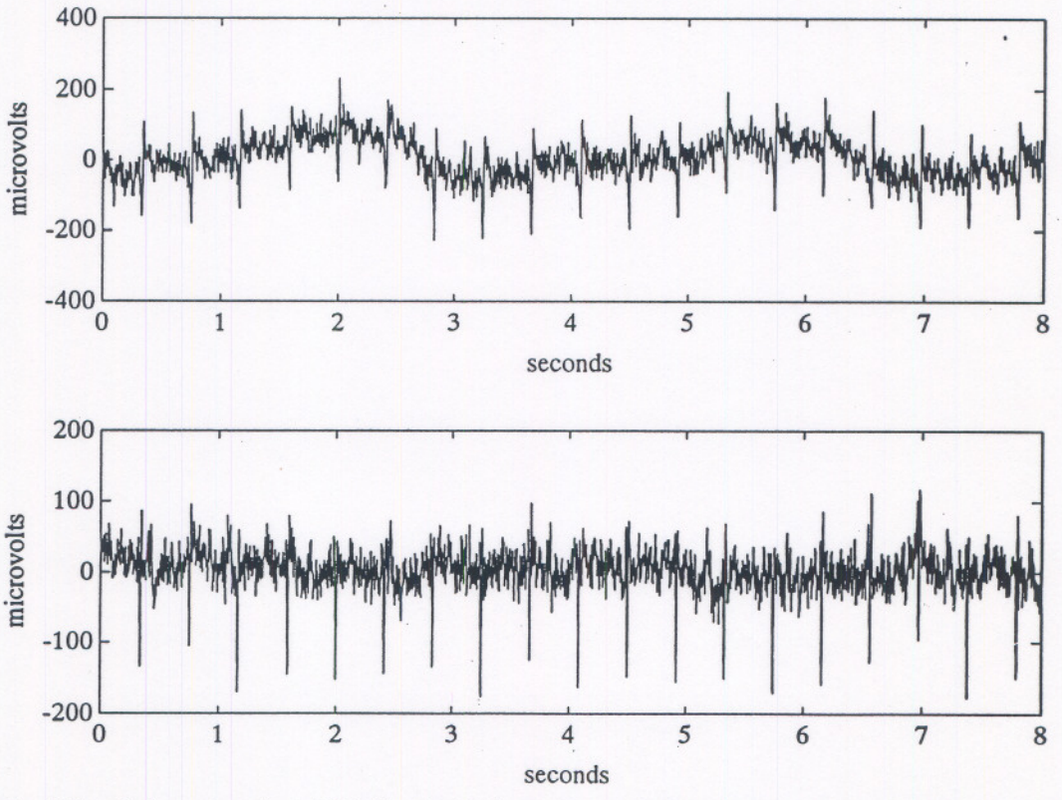


Fig 3 Two independent fetal ECG-signals obtained with the SVD-based method, using five abdominal signals.

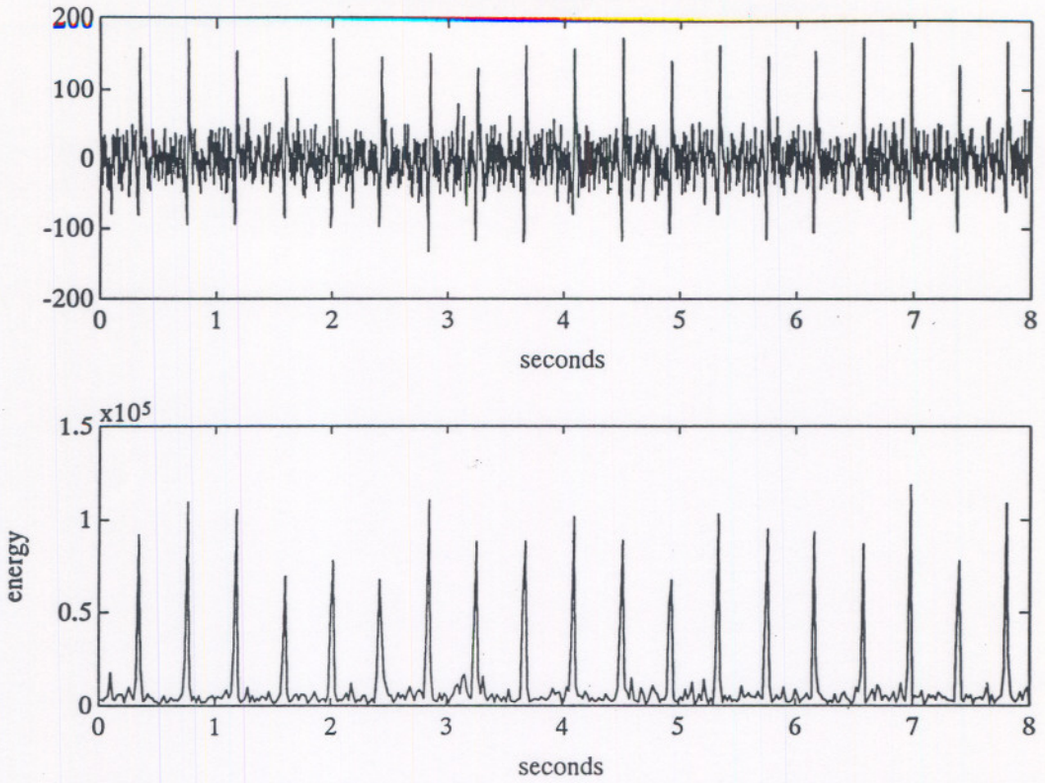


Fig 4 (a) Signal obtained by filtering the signal of Figure 3a with a high-pass filter to reduce the baseline wandering; (b) The energy-signal derived from the filtered fetal signal by plotting the sum of squares per 10 samples of this signal.

heart rate (FHR) and its beat-to-beat variability from signals as in Figure 3a. A simple thresholding method will not work, mainly because of the baseline wandering. Therefore the obtained signals must be high-pass filtered first. The result of this filtering is shown in Figure 4a. Even after filtering the signal, thresholding is quite difficult because of the uncertainty of the sign of the QRS-complexes. Therefore, a so called 'energy'-signal is constructed as follows : the filtered signal is segmented into intervals of 10 samples wide. Then the energy of each interval is computed as the sum of squares of its samples. This gives a data reduction with a factor 10 and results in an energy signal as shown in Figure 4b.

A number of methods have been derived to determine the fetal heart rate from this energy signal [1,2,12]. These methods are very robust, since they nicely detect all fetal QRS-complexes, while maternal QRS-complexes, that were not yet completely removed by the suppression step, are ignored (Figure 5a). This is an important result, because in that case the MECG must not be completely eliminated in order to determine the antepartum fetal heart rate. Figure 5b shows the instantaneous fetal heart rate, varying as a function of time over an interval of one minute.

Real-time monitoring unit

A monitoring unit for the real-time extraction of the antepartum fetal ECG from cutaneous electrode signals has been developed. The system can display in real-time some of the recorded signals, as well as some of the obtained signals in which the MECG is suppressed. It is the aim to extend the system with features such as the automatic determina-

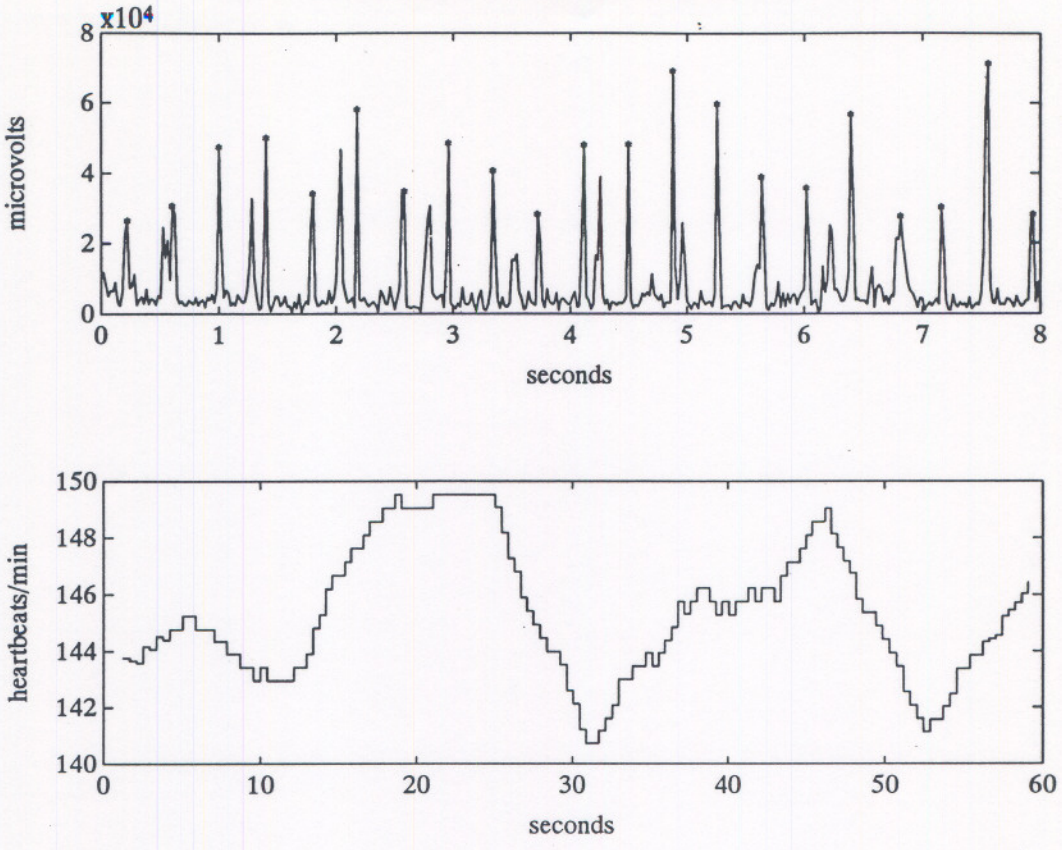


Fig 5 (a) Result of one of the FHR-detection methods, as applied to an energy-signal.(b) The variation of the fetal heart rate as a function of time.

tion of the fetal heart rate from the obtained fetal signals. At the moment the system will be used for the first clinical tests. The monitoring unit consists of an AT-compatible with a DSP-plug in board containing a TMS320C25 microprocessor and a front-end to amplify, filter and sample 8 analog recorded signals simultaneously. The system is equiped with interactive software to make the use of it by medical personnel very easy and elegant. The work is coordinated in cooperation with other European university reseach centers (Leuven, Nijmegen, Amsterdam) and has been part of the European Community Concerted Action Project 'New Methods for Perinatal Surveillance'.

Conclusions

This paper describes the results, obtained with a method to extract the antepartum Fetal Electrocardiogram (FECG) from a set of signals, recorded from electrode pairs on the skin of the mother. The method is based on the Singular Value Decomposition (SVD) of the data matrix and is successful if the electrode pairs are chosen appropriately. For this method the maternal ECG has to be picked up separately and as strong as possible. This requires - in addition to a number of electrode pairs on the maternal abdomen, close to the fetal heart - at least three electrode pairs on the thorax. It is seen from this analysis that one or more signals can be obtained, in which the maternal ECG has been suppressed sufficiently, such that the antepartum fetal ECG becomes visible. Future work will have to be performed to solve the electrode positioning problem. A real-time system for monitoring

the antepartum fetal ECG has been developed and will now be tested by medical research centers in order to do clinical fetal monitoring studies. A number of methods has been developed to derive the fetal heart rate from the cutaneously obtained MECG-free fetal signals.

References

1. Ameloot M, Claes T. *Reële-tijdsanalyse van foetale ECG-signalen*. Master's thesis Dept. of Elec. Eng., Katholieke Universiteit Leuven, Belgium, May 1992.
2. Bastijns B, De Lathauwer L, *Real-time extractie van medische informatie uit foetale hartsignalen*. Master's thesis Dept. of Elec. Eng., Katholieke Universiteit Leuven, Belgium, May 1992.
3. Bemmel JH van, Detection of weak electrocardiograms by autocorrelation and crosscorrelation of envelopes', *IEEE Trans Biomed Eng 1968; 15: 17-23*
4. Bergveld P, Meijer JH, A new technique for the suppression of the MECG. *IEEE Trans Biomed Eng 1981; 28: 348-54*
5. Callaerts D, Vanderschoot J, Vandewalle J, Sansen W, Vantrappen G, Janssens J. An adaptive on-line method for the extraction of the complete fetal electrocardiogram from cutaneous multilead recordings. *J Perinat Med 1986; 6: 421-33*
6. Callaerts D, Vanderschoot J, Vandewalle J, Sansen W, Vantrappen G, Janssens J. *Fetal electrocardiogram measuring method and equipment (FEMME)*. J Perinat Med 1987; 15: World Symposium on Computers in the Care of Mother, Fetus and Newborn, Vienna,: 33, March 1987.
7. Callaerts D, Vandewalle J. Adaptive singular value decomposition and its use for adaptive signal separation. In: *Signal Processing, scattering and operator theory and numerical methods*. Proc. of the Int. Symp. MTNS-89, Volume III, M.A. Kaashoek, J.H. van Schuppen, A.C.M. Ran (eds), 255-262, 1990.
8. Callaerts D, Sansen W, Vandewalle J, Jansen J. Description of a real-time system to extract the fetal electrocardiogram. *Clin Phys and Physiol Meas 1989; 10: 7-10*
9. Callaerts D. *Signal separation methods based on singular value decomposition and their Application to the real-time extraction of the fetal electrocardiogram from cutaneous recordings*. PhD thesis Dept. of Elec. Eng., Katholieke Universiteit Leuven, Belgium, December 1989.
10. Callaerts D, De Moor B, Vandewalle J, Sansen W. Physiological measurement: Comparison of SVD-methods to extract the Fetal Electrocardiogram from cutaneous electrode signals. *Med Biol Eng Comput 1990; 28: 217-24*
11. Callaerts D, Sansen W, Vandewalle J. *Real-time fetal ECG extraction*. Presented at the 12th Annual EMBS Int. Conference, Nov. 1-4, 1990, Philadelphia (USA).
12. Callaerts D, Sansen W, Vandewalle J. Real-time extraction of the antepartum fetal electrocardiogram. Presentation at the North Sea Conference on Biomedical Engineering - 90, Nov. 19-22, 1990, Antwerp (B).
13. Callaerts D. Singular value decomposition in digital signal processing. *Journal A, Benelux journal on automatic control 1991; 2: 11-6*
14. Eyk A van. *Abdominale Foetale ECG opname*, Techn. Univ. Twente, Enschede (NL), Rep. 1224.0093, 1976.
15. Ferrara ER, Widrow B. Fetal electrocardiogram enhancement by time- sequenced adaptive filtering. *IEEE Trans Biomed Eng 1982; 29: 458-60*
16. Golub GH, Van Loan CF. *Matrix Computations*, North Oxford Academy, 1983.
17. Hon EH, Petrie RH. Clinical value of fetal heart rate monitoring. *Clin Obstet Gynecol 1975; 4: 1-23*
18. Klema VC, Laub AJ. The singular value decompostion : Its computation and some applications. *IEEE Trans Automatic Control 1980; 2: 164-7*
19. Longini RL, Reichert TA, Yu JM et al. Near-orthogonal basis functions : A real-time fetal ECG technique. *IEEE Trans Biomed Eng 1977; 24: 39-43*
20. Oostendorp TF, van Oosterom A, Jongsma HW, van Dongen PWJ. The potential distribution generated by the fetal heart at the maternal abdomen. *J Perinat Med 1986; 4: 435-44*
21. Oostendorp T. *Modelling the fetal ECG*. PhD. thesis Med. Physics \& Biophysics, K.U. Nijmegen, Nether lands, Jan. 1989.
22. van Oosterom A, Alsters J. Removing the maternal component in the fetal ECG using singular value decomposition. In: Ruttkay-Nedecky and P. MacFarlane, Eds., *Electrocardiography '83 I*. Amsterdam, The Netherlands : Excerpta Medicine,: 171-176, 1984.
23. Oosterom A van. Spatial filtering of the fetal electrocardiogram. *J Perinat Med 1986; 6: 411-9*

24. Phelan JP. Tests of fetal wellbeing using the fetal heart rate. *Fetal monitoring: Physiology and techniques of antenatal and intrapartum assessment*. Ed. J.A.D. Spencer, Castle House Publ. Ltd., Tunbridge Wells, 1989.
25. Plonsey R. Bioelectric Phenomena. Mc Graw-Hill New York, 1969.
26. Reichert TA, Longini RL, Crowley JS, Yu JM. A noninvasive extraction of the fetal electrocardiogram. *Comput Biomed Res 1977; 10: 1-7*
27. Sureau C, Trocellier R. Etude de quelques problemes techniques en electrocardiographie foetale. *Med Elec Biol Eng 1961; 1: 181-8*
28. Vanderschoot J, Vandewalle J, Janssens J. Sansen W, Vantrappen G. Extraction of weak bioelectrical signals by means of Singular Value Decomposition. In: Bensoussan A, Lions JL, Eds. *Analysis and optimization of systems lecture notes in control and information sciences 63*, Springer Verlag, Berlin,: 434-448, 1984.
29. Vanderschoot J, Vantrappen G, Janssens J, Vandewalle J, Sansen W. A reliable method for fetal ECG extraction from abdominal recordings. In: Roger, F.H. et al, Eds. *Medical informatics europe 84 lecture notes in medical informatics 24*, Springer Verlag, Berlin,: 249-254, 1984.
30. Vanderschoot J, Callaerts D, Sansen W, Vandewalle J, Vantrappen G, Janssens J. Two methods for optimal MECG elimination and FECG detection from skin electrode signals. *IEEE Trans Biomed Eng 1987; 3: 233-43*
31. Vandewalle J, Callaerts D. Singular Value Decomposition: A powerful concept and tool in signal processing. In: McWhirter JG, Ed. *Mathematics in Signal Processing II* , pp. 539-560, Clarendon Press, Oxford, 1990.
32. Wheeler T, Murrills A, Shelley T. Measurement of the fetal heart rate during pregnancy by a new electrocardiographic technique. *Br J Obstet Gynecol 1978; 85: 12-7*
33. Widrow B et al. Adaptive noise cancelling: Principles and applications, Proc. *IEEE 1975; 63: 1692-716*