TO WHAT EXTENT THE QUALITY OF FETAL MAGNETOCARDIOGRAMS DEPENDS ON DATA FILTERING?

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Abstract: Fetal magnetocardiography (fMCG) is a non-invasive technique that allows monitoring the fetal heart activity. Two other signals, related to maternal cardiac activity and environmental magnetic noise, are simultaneously recorded during fMCG. In particular, ambient noise is the greatest obstacle to the extraction of high-quality fetal signals from fMCG, because it is an unstructured gaussian signal with large disturbances at specific frequencies. Several hardware-based techniques, such as shielded rooms, are used to reduce the great amount of ambient disturbance during acquisitions, but the use of digital filters remains the most efficient and widespread procedure to reduce noise. We analysed the different performances of the band-pass filters most commonly used in fMCG, in order to establish the most suitable one for fetal signal retrieval tasks. The reduction of ambient noise obtained for shielded and unshielded recordings was quantified, and the corresponding signal-to-noise ratio (SNR) and signal-to-distortion ratio (SDR) of the retrieved fetal signals was assessed. Sixty-six fMCG datasets of normal fetuses at different gestational age (22-37 weeks) were analysed. Among the studied filters, the band-pass filter [1 – 100 Hz] provided the best combinations of detection rates, SNR and SDR for the reconstructed fetal signals.

Introduction

Fetal magnetocardiography (fMCG) is a non-invasive technique that allows monitoring the fetal heart function. Since Kariniemi performed the first fMCG acquisition [1], it has been demonstrated that fMCG can be more effective than other clinical techniques, such as cardiotocogram (CTG) and fetal electrocardiography (fECG), for the recording of the fetal cardiac signals, in particular during the second half of gestation [2-4].

Though, the reconstruction of fetal cardiac signals is not a simple process, because they are mixed with background noise and maternal cardiac signals, which may hide the fetal traces; maternal signals, for instance, have a peak-to-peak amplitude of about one order of magnitude larger than that of fetal signals.

Therefore, digital noise filtering [5-6] is an important pre-processing step for fMCG analysis, because it may improve the performances of the techniques used to reconstruct fetal signals; however, we must keep in mind that it may also provoke the loss of important signal information and distortion of the retrieved signal morphology. Magnetically shielded rooms are also effectively used for noise attenuation, but they are very expensive and generally not ideal for a routine clinical use of fMCG [5, 7].

An optimal filtering bandwidth suitable for SNR maximization in fMCG has not been identified yet: research groups working in fMCG use a variety of band-pass filters; some authors use wide bands, with the aim of preserving the signal, but attaining a limited noise attenuation; other investigators use narrow bands that enhance noise reduction but may distort the shape of the fetal signals.

Some empirical studies on fMCG data filtering have been performed, but filters' performances have been evaluated in function of fetal traces reliability only: in fact, frequency components could not be accurately estimated because residual noise was overlapped [8].

We demonstrated in previous papers that a method based on independent component analysis (ICA) is able to reconstruct fetal traces with negligible noise contamination [9-17]. Consequently, we could calculate the spectrum of the fetal signals at different gestational ages and perform a comparative study on the quality of fMCG recordings, both shielded and unshielded, in function of the digital band-pass filter used.

Materials and Methods

Signals were recorded with a 55-channel acquisition system. The sensors, consisting of low-temperature dc-SQUIDs integrated magnetometers with sensitivity of approximately 5 $fT/Hz^{½}$ above 60 Hz, were arranged in planar geometry at fixed distances of 32 mm and covered a circular area of 415 cm^2 [7]. Sampling frequency and acquisition bandwidth were 1 kHz and [0.016 – 250.0 Hz] respectively. The MCG device operated in a magnetically shielded room to reduce background magnetic fields; acquisitions of ambient magnetic noise were performed also without shielding.

Sixty-six fMCG datasets referring to fetuses of uncomplicated pregnancies (gestational age ranging from 22 to 37 weeks) were used for this study. All

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volunteers gave their written informed consent before data acquisition, which lasted 5 to 10 minutes and provided a set of 55 simultaneous fMCG traces.

Independent component analysis (ICA) was used to reconstruct clear fetal signals from fMCG [10-13]. High-pass and low-pass filters were used to pre-process fMCG raw data before reconstructing fetal signals. In agreement with common practice, high-pass cut-off frequencies were set at 0.4, 1 and 2 Hz; low-pass cut-off frequencies were set at 80, 100 and 150 Hz. Band-pass filters were designed as Chebychev II-type digital filters, with stop-band ripple 40 dB down; in order to enhance spectral components selection, each band-pass filter was implemented combining high-pass filter and low-pass filter of different orders. Moreover, a zero-phase forward and reverse digital filtering was used in order to achieve zero phase distortion and double attenuation.

For each fMCG dataset, fetal traces with negligible noise contamination were obtained using all available 55 simultaneous recordings. Conversely, noise signals for shielded and unshielded environments were obtained from ambient acquisitions.

The effect of the band-pass filters was estimated quantifying the reduction of signal power in background noise and fetal signal; their spectral power density (PSD) in selected frequency intervals was computed and compared with the entire PSD; spectral powers for the analysed band-pass filters were inferred from the combination of data obtained for high-pass and low-pass filters. The results obtained for all fMCG datasets were divided in four groups as a function of gestational age, and the average fetal-to-noise ratio (FNR) of each group was calculated as the ratio between the average fetal signal power and the noise power in the frequency range under examination.

Finally, the improvement of the signal-to-noise (SNR) of the fMCG recordings was quantified, as well as the signal-to-distortion ratio (SDR) of the fetal traces; SDR was calculated comparing the fetal signal waveforms before and after filtering.

Results

Sufficiently good-quality fetal signals could be retrieved when FNR in fMCG recordings was greater than -3 dB, even if the fetal signals were hidden by environmental noise [14].

Figure 1 gives an example of the spectrum of the cardiac signal of a fetus at 31 weeks; the frequency content was largely included between 5 and 50 Hz. The analysis of background magnetic noise in shielded and unshielded environments demonstrated that it was not just gaussian noise: in fact, the spectrum was moderately flat, with a large percentage of energy concentrated below 5 Hz and some peaks at well-defined frequencies, generally greater than 70 Hz and more evident for unshielded recordings.

The average spectral powers of the various signals in several frequency ranges, and related percentages with respect to the total spectral power in the acquisition band, can be appreciated from Tables 1 and 2.

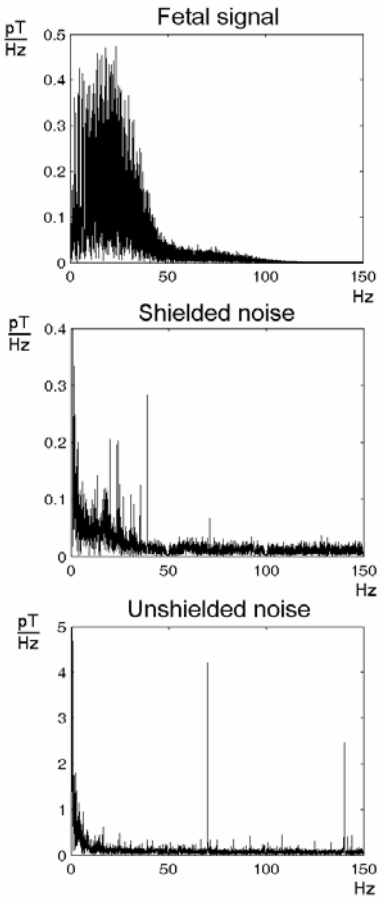

Figure 1: Examples of power spectra of fetal signals and shielded and unshielded noise. The cardiac signal refers to a fetus at 31 weeks.

Table 1: Power spectral density (PSD) of noise for shielded and unshielded environments; the figures are expressed in $fT/Hz^{½}$, and they refer to the residual signal power after band-pass filtering. Percent values (in parentheses) were calculated with respect to the total noise power in the recording bandwidth.

Frequency range (Hz)	*Residual noise PSD in shielded environment*	*Residual noise PSD in unshielded environment*
0.016 – 250	686 (100%)	2168 (100%)
0.4 – 80	636 (92.7%)	1914 (88.3%)
0.4 – 100	641 (93.5%)	1939 (89.5%)
0.4 – 150	658 (96.0%)	1995 (92.0%)
1.0 – 80	624 (91.0%)	1898 (87.6%)
1.0 – 100	629 (91.8%)	1924 (88.7%)
1.0 – 150	647 (94.3%)	1980 (91.3%)
2.0 – 80	597 (87.1%)	1860 (85.8%)
2.0 – 100	603 (87.9%)	1886 (87.0%)
2.0 – 150	621 (90.6%)	1943 (89.6%)

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It is worth noting that the fetal signal power in the bands [0.4 – 150 Hz], [1.0 – 100 Hz] and [1.0 – 80 Hz] is respectively 99.9%, 99.7% and 99.6 % of the fetal signal power contained in the recording band (Table 2). Conversely, noise reduction for the same frequency bands was 4.0%, 8.2%, 9.0% for shielded environment and 8.0%, 11.3%, 12.4% for unshielded environment (Table 1). Therefore, the percentage of background noise reduction was larger than the percent loss of the cardiac signals; in particular, the morphology and amplitude of the fetal QRS complexes were essentially unaltered. The increase of the SNR of filtered fMCG recordings can be qualitatively appreciated in the example given in Figure 2.

The results of the quantitative study on the filters' performances are summarized in Table 3. The values obtained for FNR (in shielded and unshielded environment), SNR and SDR are shown in function of gestational age. SNR values were always above 7 dB, except for the group of fetal signals included between 22 and 25 weeks and processed with the band-pass [0.4 – 150 Hz]; this filter was, in general, the least effective to reduce noise and had the worst detection rate before 32 weeks, but it guaranteed the best performance in terms of signal distortion.

The strongest de-noising was achieved with the filter [1.0 – 80 Hz], which provided high SNR and the best detection rates among all analyzed band-pass filters; however, it produced some waveform distortion with SDR always below 26 dB.

Table 2: PSD of fetal signals in the same frequency bands as in Table 1; values, expressed in $fT/Hz^{½}$, are given as averages on groups of fetal signals belonging to the same gestational period. Percent values (in parentheses) were calculated with respect to the total signal power in the recording bandwidth.

	Gestational age in weeks (number of datasets)			
Frequency range (Hz)	22-25 (13)	26-29 (15)	30-33 (18)	34-37 (20)
0.016 – 250	456 (100%)	703 (100%)	1075 (100%)	1409 (100%)
0.4 – 80	454 (99.6%)	702 (99.8%)	1073 (99.8%)	1406 (99.8%)
0.4 – 100	455 (99.8%)	702 (99.9%)	1074 (99.9%)	1408 (99.9%)
0.4 – 150	456 (99.9%)	703 (99.9%)	1074 (100%)	1408 (99.9%)
1.0 – 80	453 (99.4%)	701 (99.6%)	1071 (99.7%)	1403 (99.6%)
1.0 – 100	454 (99.6%)	702 (99.8%)	1072 (99.8%)	1405 (99.7%)
1.0 – 150	455 (99.7%)	702 (99.8%)	1073 (99.8%)	1405 (99.7%)
2.0 – 80	451 (98.8%)	696 (99.0%)	1066 (99.2%)	1393 (98.8%)
2.0 – 100	452 (99.1%)	697 (99.2%)	1067 (99.3%)	1394 (98.9%)
2.0 – 150	452 (99.2%)	698 (99.2%)	1068 (99.4%)	1395 (99.0%)

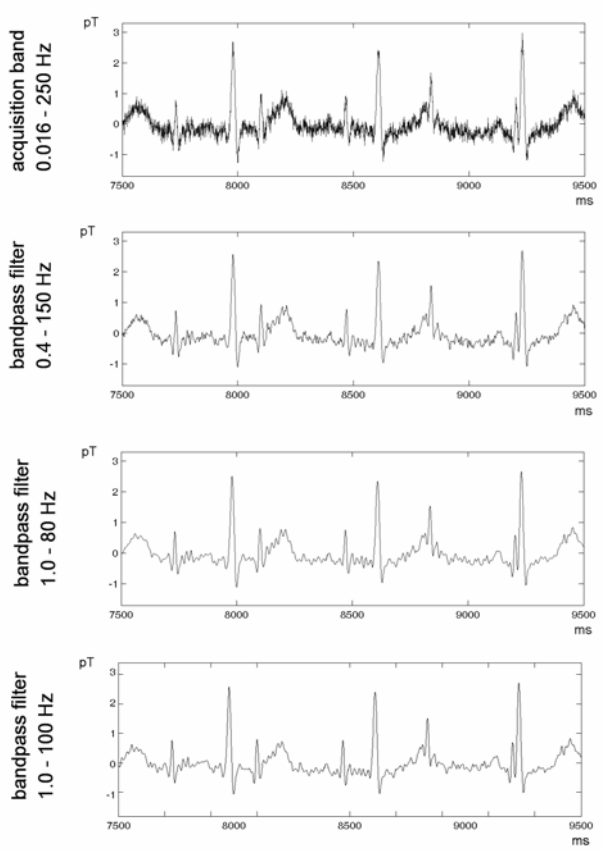

Figure 2: Examples of one fMCG recording (fetus at 33 weeks) processed with the analyzed band-pass filters. The upper trace shows the original recording (central sensor of the MCG array); the other strips illustrate how the same recording appears after de-noising with the various filters.

Conversely, the band-pass filter [1.0 – 100 Hz] produced very little waveform distortion (SDR always greater than 30 dB) and concurrently ensured substantial noise reduction (7.4 dB < SNR < 12 dB) with high fetal signal power (minimum PSD value 99.6%).

Figure 3 shows the effect of the analyzed band-pass filters on the fetal traces reconstructed from the dataset to which the recording shown in Figure 2 belongs.

Discussion

FMCG is at the moment the best method for the non-invasive recording of the time-course of the fetal cardiac activity, especially during the second half of pregnancy. FMCG allows the qualitative and quantitative evaluation of fetal cardiac signals, and the monitoring of the electrophysiological development of the fetal heart.

The development of new acquisition systems working in unshielded environment and/or suitable for bedside recordings in a hospital setting [18] requires that a general standardization of the procedures is achieved. A first step towards the homogenization of the techniques for the processing of fMCG recordings regards the definition of an optimal de-noising

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procedure, given its importance to improve the effectiveness of methods used for the retrieval of fetal cardiac signals.

Table 3: Quantitative evaluation of the most commonly used band-pass filters. The fetal-to-noise ratio (FNR, given in dB) was calculated for fMCG data sets grouped in gestational periods and with respect to shielded and unshielded environments. For each gestational period, the average detection rate, SNR and SDR, expressed in dB, of reconstructed fetal signals are given.

Gestational age	22-25	26-29	30-33	34-37
Acquisition band: 0.016-250 Hz				
detection rate	15%	27%	83%	100%
FNR – unshielded	-13.5	-8.9	-4.9	-1.9
FNR – shielded	-3.5	1.1	5.1	8.0
SNR – fetal	5.1	6.9	8.4	9.7
Band-pass filtering: 0.4-150 Hz				
detection rate	31%	53%	94%	100%
FNR – unshielded	-12.8	-8.2	-4.2	-1.2
FNR – shielded	-3.2	1.5	5.5	8.4
SNR – shielded	5.7	7.9	9.3	10.5
SDR	41.7	41.9	43.6	42.7
Band-pass filtering: 1.0-80 Hz				
detection rate	39%	60%	100%	100%
FNR – unshielded	-12.4	-7.7	-3.8	-0.8
FNR – shielded	-2.8	1.9	5.9	8.8
SNR – shielded	7.6	11.1	11.4	13.1
SDR	25.8	25.9	26.0	25.4
Band-pass filtering: 1.0-100 Hz				
detection rate	46%	60%	100%	100%
FNR – unshielded	-12.5	-7.9	-3.9	-0.9
FNR – shielded	-2.8	1.8	5.8	8.8
SNR – shielded	7.4	9.7	10.4	12.0
SDR	32.4	31.1	31.2	30.4

In the present study, several band-pass filters were analysed on the basis of the frequency content of both ambient field noise, recorded inside and outside shielded room, and fetal signals, separated with ICA from shielded fMCG datasets.

Although the intensity of unshielded noise was, in general, one order of magnitude greater than that of magnetic noise inside a shielded room, the frequency content of those two signals was very similar (Figure 1). Consequently, it is not necessary to identify different procedures to filter fMCG recorded inside and outside a shielded room: in fact, the same filter configuration can be used for both settings.

Filter performances proved to be fairly similar from a qualitative point of view, as confirmed by the high values of fetal PSD obtained for all gestational periods (Table 3). However, when the effect of those filters was evaluated quantitatively, a few differences were found in the detection rates, SNR and SDR of retrieved fetal traces. We could identify what filters might be more useful for clinical application using thresholds for SNR and SDR: in fact, only those filters allowing the extraction of fetal signals with SNR larger than 5 dB and SDR larger than 30 dB were taken into account.

As expected, the highest de-noising was achieved with the band-pass filter [1.0 – 80 Hz], but this also entailed some distortion of fetal signal waveforms; conversely, the filter [0.4 – 150 Hz] preserved the original shape of fetal signals, but noise reduction was relatively small. In contrast, the band-pass filter [1.0 – 100 Hz] provided the best compromise between SNR and SDR for all gestational ages, together with the best detection rates.

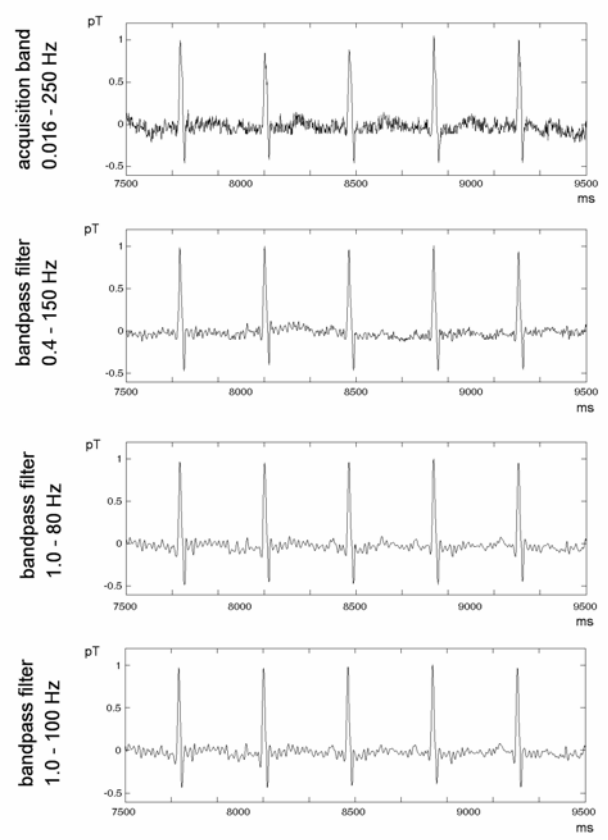

Figure 3: Fetal cardiac traces obtained from the recordings in Figure 2. They allow appreciating the noise decrease achieved with the different band-pass filters.

Conclusions

Our findings show that digital band-pass filters must be chosen carefully to recover maximum information on fetal cardiac activity without altering signal shape. Given that no substantial differences in frequency content were found between shielded and unshielded noise, a common filtering might be used for both shielded and unshielded fMCG recordings.

All filters succeeded in strongly reducing noise without substantially altering the frequency content of fetal signals. However, the band-pass [1.0 – 100 Hz] should be preferred, because it combines high noise reduction with small power loss and negligible distortion in the fetal signals. The use of an appropriate

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filtering in combination with ICA processing might even permit a lowering of the gestational age limit for the retrieval of reliable fetal magnetocardiograms in a hospital setting.

References

[1] KARINIEMI V., AHOPELTO J., KARP P.J. and KATILA T.E. (1974): "The fetal magnetocardiogram", J *Perinat Med*, **2**, pp. 214-216

[2] LEWIS M.J. (2003): "Review of electromagnetic source investigations of the fetal heart" *Med Eng Phys*, **25**, pp. 801-810

[3] TAYLOR M.J., SMITH M.J., THOMAS M., GREEN A.R., CHENG F., OSEKU-AFFUL S., WEE L.Y., FISK N.M. and GARDINER H.M. (2003): "Non-invasive fetal electrocardiography in singleton and multiple pregnancies" *Br J Obstet Gynaecol*, **110**, pp. 668-678

[4] STINSTRA J.G. and PETERS M.J. (2002): "The influence of fetoabdominal tissues on fetal ECGs and MCGs", *Arch Physiol Biochem*, **110**, pp. 165-176

[5] VOLEGOV P., MATLACHOV A., MOSHER J., ESPY M.A. and KRAUS R.H. (2004): "Noise-free magnetoencephalography recordings of brain function", *Phys Med Biol*, **49**, pp. 2117-2128

[6] HILGENFELD B., STRAHMEL E., NOWAK H. and HAUEISEN J. (2003): "Active magnetic shielding for biomagnetic measurement using spatial gradient fields", *Physiol Meas*, **24**, pp. 661-669

[7] DELLA PENNA S., DEL GRATTA C., ERNE S.N., GRANATA C., PASQUARELLI A., PIZZELLA V., ROSSI R., RUSSO M., TORQUATI K. and ROMANI G.L.(2000): "Biomagnetic systems for clinical use", *Philosoph Magaz*, **80**, pp. 937-948

[8] STINSTRA J.G., PETERS M.J. and QUARTERO H.W.P. (2000): "Extracting reliable data from the fetal MCG", Proc. of BIOMAG 2000, *International Conference on Biomagnetism 2000*, pp. 591-594

[9] COMON P. (1994) "Independent component analysis - a new concept?" *Signal Processing*, 36, 287-14

[10] HYVÄRINEN A and OJA E. (2000): "Independent component analysis: algorithms and applications", *Neural Networks*, **13**, pp. 411-430

[11] HYVÄRINEN A. (1999): "Fast and robust fixed-point algorithms for independent component analysis", *IEEE T Neural Network*, **10**, pp. 626-634

[12] COMANI S., MANTINI D., PENNESI P., LAGATTA A. and CANCELLIERI G. (2004): "Independent component analysis: fetal signal reconstruction from magnetocardiographic recordings", *Comput Meth Prog Biomed*, **75**, pp. 163-177

[13] MANTINI D, COMANI S, PENNESI P. and CANCELLIERI G.. (2004): "Tailoring of the independent component analysis to multi-channel fMCG recordings for an optimal reconstruction of the fetal cardiac signal" *Biomed Tech*, **48**, pp. 186-188

[14] COMANI S., MANTINI D., LAGATTA A., ESPOSITO F., DI LUZIO S. and ROMANI G.L. (2004): "Time course reconstruction of fetal cardiac signals from fMCG: Independent Component Analysis vs. Adaptive Maternal Beat Subtraction", *Physiol Meas*, **25**, pp. 1305-1321

[15] COMANI S., MANTINI D., ALLEVA G., DI LUZIO S. and ROMANI G.L. (2004): "Fetal magnetocardiographic mapping using independent component analysis" *Physiol Meas*, **25**, pp. 1459-1472

[16] COMANI S., LIBERATI M., MANTINI D., GABRIELE E., BRISINDA D., DI LUZIO S., FENICI R. and ROMANI G.L. (2004): "Characterization of fetal arrhythmias by means of fetal magnetocardiography in three cases of difficult ultrasonographic imaging", *Pacing Clin Electrophysiol*, **27**, pp. 1647-1655

[17] COMANI S., MANTINI D., ALLEVA G., GABRIELE E., LIBERATI M. and ROMANI G.L. (2004): "Simultaneous monitoring of separate fetal magnetocardiographic signals in twin pregnancy", *Physiol Meas*; **at press**.

[18] BRISINDA D., COMANI S., MELONI A.M., ALLEVA G., MANTINI D. and FENICI R. (2005): "Multichannel Mapping of Fetal Magnetocardiogram in an Unshielded Hospital Setting", *Prenat Diag*, **25**, pp. 376-382

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