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Jukka Nenonen
Risto J. Ilmoniemi
Toivo Katila

Extracting reliable data from the fetal MCG

J.G. Stinstra[1], M.J. Peters[1], and H.W.P. Quartero[2]

[1]*University of Twente, Enschede, The Netherlands;* [2]*Hospital MST, Enschede, The Netherlands*

1. Introduction

Extracting reliable information from a fetal MCG measured before the 24th week of gestation is hampered due to the poor signal-to-noise ratio. Thence, the recorded signals need to be processed in order to separate noise and signal, and need to be displayed in such a way that a reliable diagnosis can be made. No signal processing can be performed without making assumptions on either noise or signal. These assumptions have to be chosen carefully so that they do not interfere with the diagnosis made.

2. Method

Fetal MCGs are measured using a 19-channel low-Tc gradiometer system in a magnetically shielded room. The signals are recorded using a sample frequency of 1kHz and stored on the harddisk of a computer. After recording, the data is digitally processed to obtain reliable cardiac waveforms.

Since noise is assumed to be uncorrelated to the cardiac pacing, averaging the cardiac waveforms will enhance the signal-to-noise ratio as the noise is averaged out. This averaging procedure is carried out with the R-peaks as trigger for the cardiac beat. To be able to detect the correct time instants of R-peaks, the signal is filtered by a band pass filter of 10 to 40Hz. Because most of the signal energy of the R-peak is found between these frequencies, it enhances the signal-to-noise ratio before R-peak detection. Nevertheless, the filtered signal is not used for the averaging procedure itself, because the filter transforms the cardiac complexes.

In order to obtain the proper filter frequencies to filter the fetal MCG different frequency ranges are applied and tested. For the high-pass filter, cut-off frequencies of 2Hz and 4Hz are investigated and for the low-pass filter, cut-off frequencies of 100Hz, 75Hz, and 50Hz are tested. The filters are digitally implemented as Finite Impulse Response filters.

It is difficult to assess which aspects of the averaged cardiac waveform are significant and which might be due to noise and therefore not to be interpreted. It is for example not clear whether a bump in the cardiogram is caused by averaging noise or by a genuine effect in the cardiac waveform. To make the interpretation of the average easier, a 98% confidence interval is evaluated for each time instant of the average. It is assumed that the actual cardiac waveform lies between the upper and lower 98%-confidence curves (see figure 1). Details that are smaller than the interval between the confidence limits cannot be trusted and are therefore eliminated by smoothing the signal (the red line in figure 1).

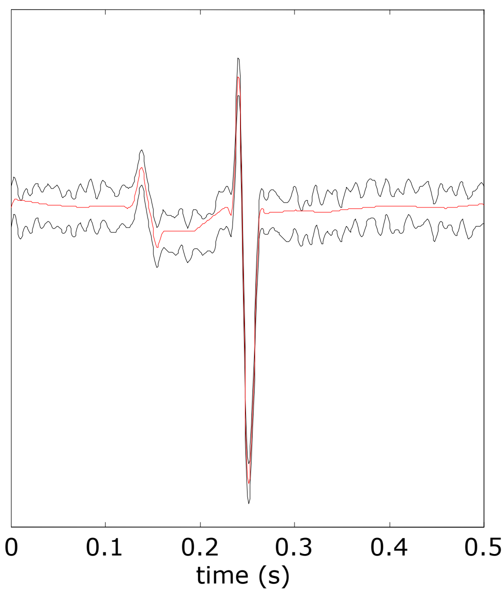

Figure 1: *Confidence interval (98%) and in between the reconstructed cardiac waveform (red line).*

The most probable cardiac waveform is still the original average, however all cardiac waveforms, which are between the confidence limits could be solutions as well. As physicians tend to interpret a straight line as having "no information", straight lines are used to replace bumps that are smaller than the interval between the confidence limits. These smoothed cardiac waveforms can be used for diagnostic purposes, because the actual information is statistically relevant. Only those aspects that have small chance of being caused by noise are depicted. This step of smoothing the cardiac waveform is implemented as a post-processing step after the average has been constructed.

The algorithm used to replace sections of the signal with straight lines, starts by subdividing the signal into sections. Each section starts at a local minimum or maximum and ends at the subsequent one. If the beginning and the ending of a section are more than the confidence interval apart, the section remains untouched. The other sections are selected for smoothing. In the next step successive sections that are selected for smoothing, are joint to form a single section. Each section is now described by a straight line. In figure 4, such a reconstruction is shown.

To calculate the confidence interval it is assumed that the "noise" superimposed on the fetal MCG is gaussian distributed. To validate this assumption the distribution is tested for each time instant by a chi-square-goodness-of-fit test (the time instants are 1ms apart). In this test the distribution per time instant is compared to the gaussian distribution. The chi-square-goodness-of-fit test results in values that have to be chi-square distributed.

3. Results

To check whether the filtering between 2Hz and 100Hz is allowed, different filters are used to test whether they influence the shape of the cardiac waveform. For this purpose, a fetal MCG is taken of a 38-weeks-old fetus having a high signal-to-noise ratio. In figure 2, the influences of both the low-pass and the high-pass filter are shown. Visual inspection of the results shows that a cut-off frequency of less than 100Hz for the low-pass filter does influence the shape of the cardiac wave. The same is true for a high-pass cut-off frequency higher than 2Hz. Therefore a bandwidth of 2 - 100Hz is chosen as a proper one.

The procedure of coherent averaging and post-processing the cardiac complex is applied to a fetal MCG of a 21-weeks-old fetus, which was diagnosed by means of ultrasound with a congenital heart disease (endocardial fibroelastosi of the right ventricle, aortic stenosis and ventricular septal defect). The measurement is shown in figure 3. In the data shown the maternal complexes are suppressed by coherently averaging the maternal cardiac complexes using the maternal ECG as a trigger and subsequently subtraction of the maternal complexes.

As can be noticed, the R-peaks are barely visible and they are the only part of the cardiac complex recognizable in the 'raw' signal. For the signal three averages are calculated (see figure 4); the first is an average of the raw signal, the next is an average after band-pass filtering the signal between 2Hz and 100Hz and the third is the latter after replacing sections that are statistically insignificant with straight lines. Comparison of the original average and the enhanced averages shows the same features in both complexes, however removal of the non-significant parts makes the interpretation straightforward. In the averages an additional peak in front of the QRS complex is visible having an amplitude just slightly larger than the confidence interval, which may be due to the fetal condition. Repeating the same signal processing procedure to a fetal MCG measured in the 30th week of gestation did not show this additional peak.

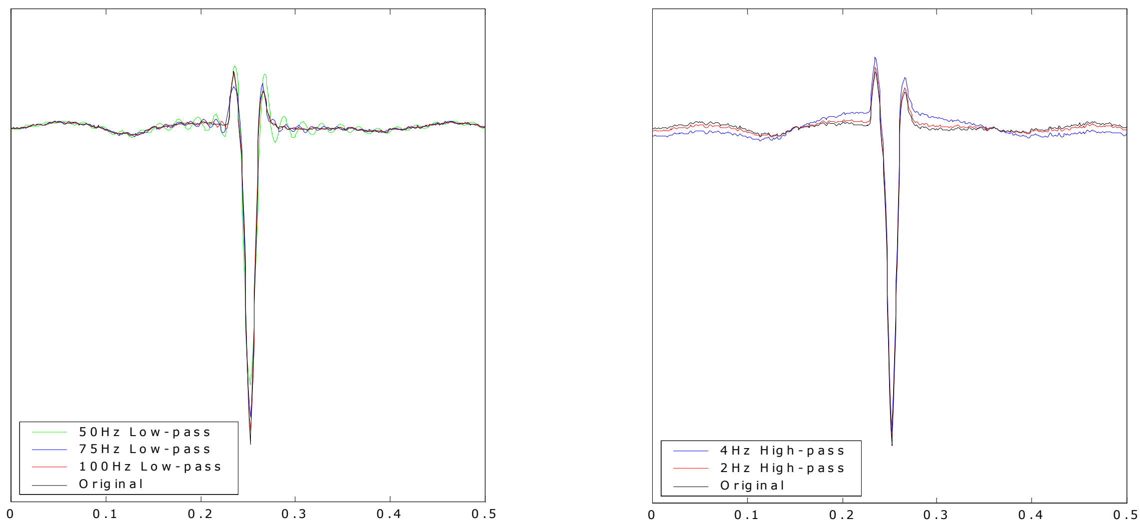

Figure 2: *The effect of applying a low-pass filter on the shape of the averaged complex (left), the effect of applying a high-pass filter on the shape of the averaged complex (right). As source a fetal MCG of a 38-weeks-old fetus is used with a high signal-to-noise ratio.*

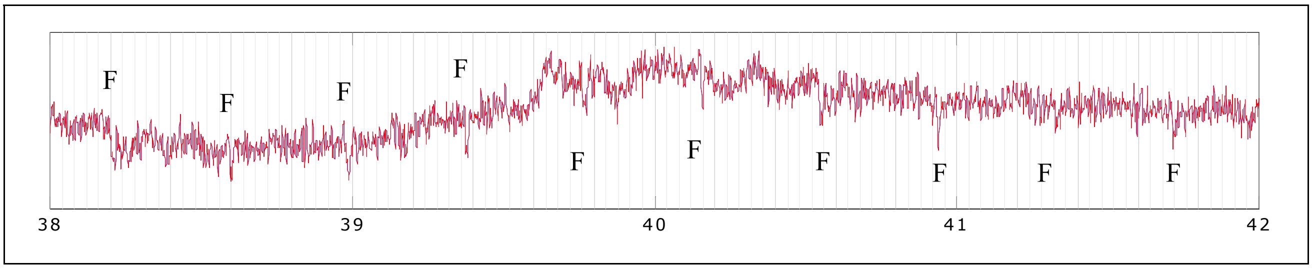

Figure 3: *The "raw" fetal MCG signal recorded in the 21st week (upper row). The maternal MCG contribution has been removed from the signal.*

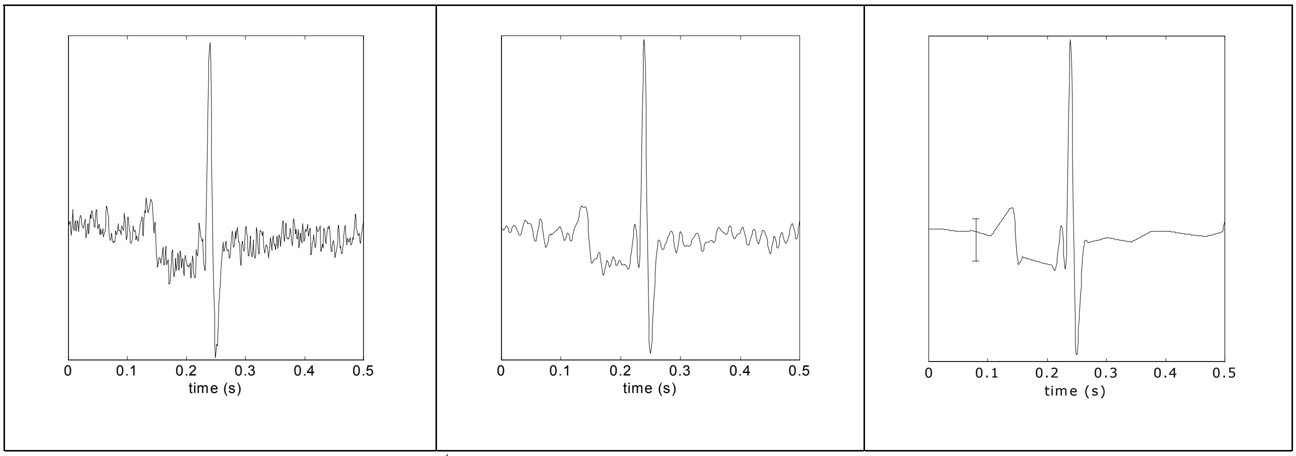

Figure 4: *Averages made in the 21st week of gestation (upper row). The first column contains the averages without filtering the signal prior to averaging. The second row contains the averages after first applying a band-pass filter of 2 till 100Hz. The third row is the average after straightening those areas with not significant fluctuations. The 98% confidence interval is indicated in the figure.*

The width of the QRS-complex and the P-wave are determined for both measurements. The width of the P-wave is 39ms (21 weeks) and 49ms (30 weeks), the width of the QRS-complex is 39ms (21 weeks) and 55ms (30 weeks). Comparison with the reference data of the database [1] shows that these time intervals are within normal range.

In calculating the confidence interval it is assumed that the "noise" is gaussian distributed. To verify this assumption a distribution diagram is made of the fetal MCG measured during the 21st week of gestation. For each cardiac complex the corresponding samples are gathered and a histogram is made of their distribution. In figure 5, this distribution is drawn for each time instant in the averaged cardiac waveform. The distributions are more or less the same, apart from a shift in the mean value of the distribution.

Each distribution is subsequently tested of being a normal distribution by means of the chi-square-goodness-of-fit test. The results of the tests are displayed in a histogram (see figure 6). And indeed, one can conclude that the noise is gaussian distributed.

4. Discussion

Usage of the confidence interval in the averaging procedure proves to be helpful in interpreting signals. Another way of enhancing the signals can be obtained by including more complexes into the averaging procedure to reduce the noise level, however the question is whether the heart complexes remain the same over a longer period of time. Especially in the early weeks of gestation the fetus is able to move freely within the uterus. Measurements suggest that the periods in which movements are absent have a mean duration of 4 minutes (with a maximum of 11 minutes) for the gestational age of 8-20 weeks, 5 minutes (maximal 17 minutes) for weeks 20-30, thereby limiting the number of complexes that can be used [2].

The analysis of the signals of the fetus with congenital heart disease used in this paper results in an additional peak in front of the QRS-complex in the magnetocardiogram measured in the 21st week of gestation. Apart from this finding the magnetocardiogram is normal. Thus, the diagnosis of this congenital disease cannot be confirmed by fetal MCG.

5. References

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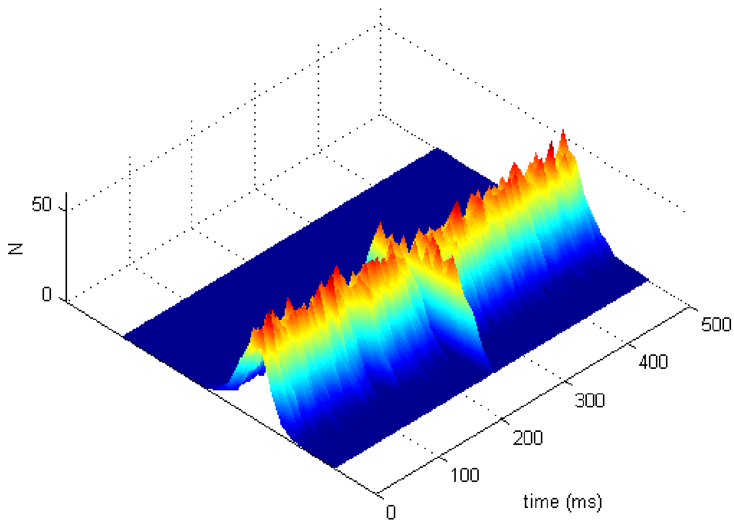

Figure 5: *The distribution function of the cardiac waveforms used to construct an average (upper figure). The histogram of 150 subsequent cardiac waveforms is displayed for each time sample in the cardiac waveform.*

Figure 6: *For each distribution (500 in total) a chi-square-goodness-of-fit test is performed, the results of all 500 tests are summarized in a histogram.*