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Real-time Access of Magnetoencephalographic / -cardiographic Data: Technical Realization & Application to Online Fetal Heart Rate Recording

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Abstract – **Current standard magnetoencephalographic and -cardiographic systems do not allow real-time access to the measured data. We developed a software solution for real-time access and used it to create an online fetal heart rate monitor.**

I. INTRODUCTION

Fetal magnetoencephalography (fMEG) based on SQUID-technology is an emerging application in the biomedical field. Based on the development of a dedicated fetal system, fMEG investigations can be performed on a routine basis. However, certain security issues must first be addressed, especially during investigations of fetuses at risk. Continuously monitoring the heart rate of fetuses at risk is particularly important because it is a possible indicator of fetal complications. Due to the MEG technique, current heart rate monitors are not usable in combination with fMEG. One approach to enable real-time heart rate monitoring in fMEG is the continual analysis of data provided by the fMEG system during investigations.

Evidently, two fundamental features impact the quality of such a real-time fetal and maternal heart rate monitor. The first feature is access of fMEG data in real-time. This access is based on software development in collaboration with the manufacturer of the fMEG system (VSM MedTech Ltd., Vancouver, Canada). The second feature is an algorithm that extracts both fetal and maternal heart rate from measured magnetocardiographic signals (MCG). This algorithm must separate maternal and fetal heart signals in the presence of several interfering noise sources, e.g. maternal and fetal movements, and it must cope with online data input. In conclusion, our research was aimed at adapting real-time access to our requirements and realizing the algorithm.

II. METHODS

We first describe the fMEG system, followed by a discussion of two features of real-time access: general access and transfer of fMEG data to the analysis. Our main focus is the investigation of the delay time between the actual recorded data and its transfer to the analysis program. In the last section, we explain the algorithm used to extract the heart rate.

A. *fMEG System*

Measurements were performed with a 151-channel SQUID fMEG system (SARA) [1]. SARA is a stationary, floor-mounted instrument where the mother sits and leans her abdomen against an anatomically shaped sensing surface. This design is inherently safe. The mother is comfortable and can gain easy access to or dismount from the system. The system is in a magnetically shielded room and is equipped with high-order synthetic gradiometer noise cancellation, which effectively eliminates the vibrational noise transmitted by the mother. An array of 151 SQUID sensors covers the mother's anterior abdominal surface, from the perineum to the top of the uterus (in late gestation). The primary sensor flux transformers are axial first-order gradiometers with 8cm baselines. The nominal SQUID sensor noise density is 5 fT/√Hz. A set of 29 reference SQUID sensors is incorporated for attenuation of environmental and vibrational noise. The primary sensor array is curved to fit the pregnant abdomen, covering a region of approximately 45cm high and 33cm wide, with an area of 1300cm^2 and inclined at 45°. Dependent on the distribution of the sensors, maternal and fetal heart signals are recorded simultaneously with the fMEG signal (Fig. 1).

B. *Real-time Access of fMEG Data*

In typical MEG investigations, MEG data are recorded and saved by a control program. Afterwards, these data can be analyzed offline. For online data access, a support program (RealTime) creates a shared memory segment in the memory. Thereby, the control program collects and subsequently writes fMEG data (in the form of packets) into the shared memory segment during recordings. The support program constantly checks for packets within the storage. If a packet is present, it will be read by the support program.

We modified the support program (written in C/C++) in order to make fMEG data accessible to other applications. Due to our modifications, we are able to arbitrarily address each single sensor and data value.

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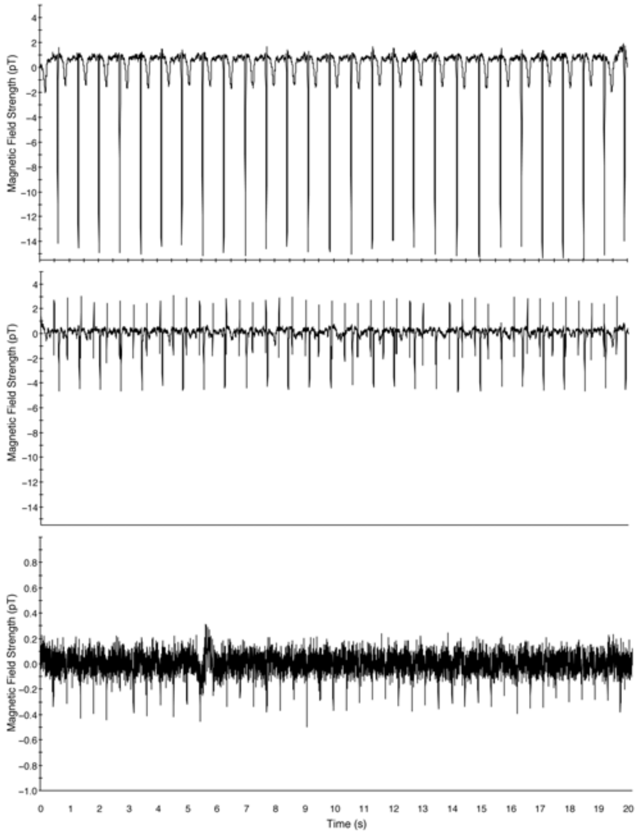

Fig. 1. Three typical magnetic channels during a recording session. Upper row: channel mainly containing maternal MCG, middle row: channel containing mixture of maternal and fetal MCG, bottom row: channel containing mainly fetal MCG. The bottom row is displayed with a different scaling.

C. *Transfer of fMEG data*

Because the heart rate extraction algorithm was developed in MATLAB (MathWorks Inc., MA, USA), we created an interface that enables bidirectional communication between C/C++ (the real-time access) and MATLAB (the extraction algorithm) with C/C++. This makes the interface also usable for other online application.

For our purpose, the interface completely controls the data transfer between the real-time access and the algorithm (see Fig. 2). As described above, fMEG data are written packet-wise into shared memory. The modified support program reads and delivers these data sample by sample to the interface. The interface collects a certain amount of fMEG data and transfers these data packet-wise to the algorithm (MATLAB). A packet-wise (constantly 300 samples per sensor per packet) data transfer is necessary due to algorithm's mode of operation. (Note: These 'packets' are independent of the packets written into shared memory). After MATLAB calculations are complete, however, the interface receives a value indicating the number of already transferred fMEG data samples that are again required for the next calculation. In other words, the algorithm needs a varying amount of data from the previous step. As such, the interface accomplishes the desired goal by assembling the next 'packet' as required (old, requested data plus new data). Finally, this new 'packet' is again transferred to the algorithm. In doing so, the interface presents the fMEG data in a sliding data window, as required by the algorithm.

D. *Source and Measurement of Delays*

The source of delays is clearly given by the packet-wise data transfer of the current system software (control program). Due to this software's mode of operation, a packet can never be transferred before it is completely filled with data samples. This fact, combined with a fixed packet size, automatically results in delays. In addition, the delays will be dependent on both the sample rate and the number of recorded channels because these two factors determine the time needed to completely fill a packet with data samples.

For delay measurements, we used a signal generator to apply a square wave signal to the MEG sensors and to the parallel port of the computer measuring the time differences. The program used for time measurement was adapted to gain access to both the signal recorded by the MEG system (subsequently read by the real-time access) and the parallel port. This ensures that the time difference between the rising edge of the delayed and the original, undelayed signal can be measured. Clearly, this time difference equals the delay between signal occurrence and the ability to evaluate the signal. Possible misalignments were prevented using a 1Hz square wave signal because the online delay is much less than 1s. Furthermore, our system environment provided sub-ms resolution.

E. *Online Maternal and Fetal Heart Rate Detection*

The basis of the maternal and fetal heart rate detection is to find the corresponding R-wave from the energy transform of the data. The energy transform is defined in [2] as

$$J(n)=\sum_{\tau=n}^{n+q-1}\sum_{j=1}^{m}(x_j(\tau)-x_j(\tau-1))^2 , \qquad (1)$$

where x_j is the signal at the jth sensor, n is the discrete time, m is the number of sensors, q is the transformation window, and τ is a nuisance variable.

In our case, we compute two energy transforms based on the assumption that the m sensors can be divided as $m=m_r+m_l$, where m_r sensors are reference sensors assumed to contain mostly maternal signal, and the remaining m_l sensors are used for the identification of the fetal component. Hence, we calculate the corresponding energy transforms $J_r(n)$ and $J_l(n)$, and from them we compute the maternal and fetal R-wave, respectively.

The detection of the R-wave in either $J_r(n)$ or $J_l(n)$ is achieved through a Hilbert transform detector [3] of the form

$$\theta = 0.4\ \max\{\mathrm{y(n)}\}, \qquad (2)$$

where θ is the threshold of the detector, and $y(n)$ is the envelope signal. This last one is approximated, by

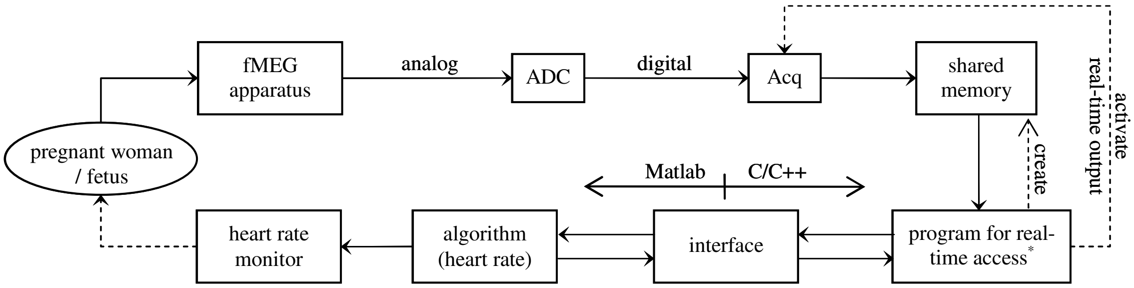

Fig. 2. Flowchart depicting both the application of the real-time access in real-time heart rate monitoring and the flow of fMEG data through all involved entities. (ADC – analog/digital converter, Acq – control program, * – support program)

$y(n) \approx |h_1(n)| + |h_2(n)|$, where $h_1(n)$ and $h_2(n)$ are orthogonal filters, i.e.

$$h_1(n) = J_k(n) - J_k(n-6), \tag{3}$$

and

$$h_2(n) = J_k(n) - J_k(n-2) - J_k(n-6) - J_k(n-8), \tag{4}$$

where the subscript k indicates r or l, depending on the R-wave to be detected.

Finally, the procedure consists in the detection of maternal R-wave using $J_r(n)$ to later detect the fetal one from $J_l(n)$. Since the maternal component is likely to appear also in $J_l(n)$, the preliminary values detected from the maternal R-wave are discarded in $J_l(n)$, leaving only those corresponding to the fetal R-waves.

F. *Offline Maternal and Fetal Heart Rate Detection*

For the offline detection of maternal and fetal heart signals, we used a template matching algorithm followed by orthogonal projection to attenuate the detected signal. This procedure is used on a regular basis to attenuate the maternal and fetal MCG during fMEG recordings and, therefore, allows the detection of maternal and fetal heart signals [4].

III. RESULTS

Fig. 3 summarizes the results of delay measurements. Our findings confirm that the delays are dependent on the sampling frequency and the number of recorded channels. Furthermore, regular jitters occur during data transfer, resulting in delays ranging from 1ms to 100-330ms (maximum delays for 246 channels). All together, it is possible that the algorithm gains access to a data sample in less than or equal to 100ms (for sample rates greater than or equal to 625Hz).

As an example, we calculated the heart rate of a dataset (gestational age 36 weeks, recording length 360s, sample rate 312.5 Hz) offline and compared it to the result of the online algorithm (see Fig. 4). Please note that in order to evaluate the online algorithm, we delivered fMEG data to the online algorithm identical as during an actual recording, thus simulating an online situation.

Overall, the online algorithm detected the maternal heart rate as well as the offline algorithm. However, for the fetal heart rate, there are some differences. Specifically, short periods (one QRS complex) were sometimes not detected, but the overall performance was similar to the offline algorithm.

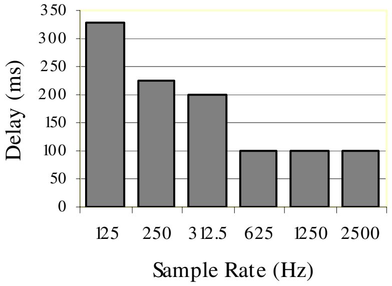

Fig. 3. Maximum delays (dependent on sampling rate) for recordings with 246 channels. Tests involving 181 channels revealed a greater maximal delay (about 400ms) at 125Hz (not shown).

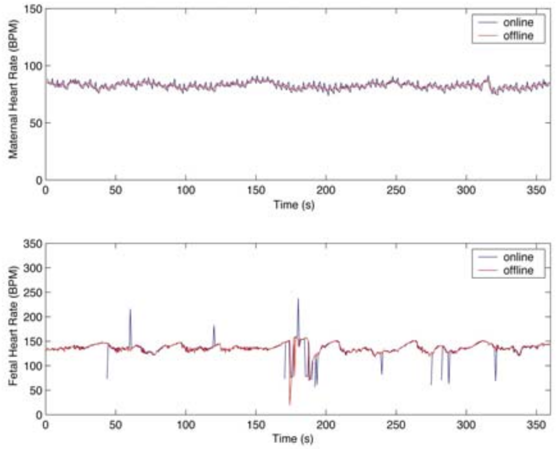

Fig. 4. Comparison of online and offline analysis of maternal and fetal heart rate. (BPM – beats per minute)

IV. DISCUSSION

The reason for the aforementioned jitters within the delays can be explained as follows. If there is a particular signal within a data stream, two extreme possibilities can occur:

- The signal is just in time to be sampled by the system and included as the last dataset entry of the last packet written into shared memory. This packet is then immediately accessible, resulting in a delay of less than 1ms (independent of sample rate and number of recorded channels).
- The signal occurs shortly after the last packet is written into shared memory. In this case, a specific amount of time is necessary to collect enough additional data to completely fill the next packet written into shared memory, resulting in a delay of 100-330ms (dependent on sample rate and number of recorded channels).

Nevertheless, it is possible to guarantee a constant delay of 100ms for sample rates greater than or equal to 625Hz. In conclusion, the largest number of sensors and highest possible sample rate should be used to minimize the delay, but the minimal constant delay remains at 100ms.

The offline and online analysis of fetal heart rate resulted in similar findings. As such, it will be possible to test the online algorithm in a real-time environment.

In addition, the developed real-time access can be used on all systems with the same electronics and for alternative applications. One possible application is brain computer interface research.

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