FETAL MAGNETOCARDIOGRAPH DESIGNED FOR UNSHIELDED ENVIRONMENTS

Bondarenko N[1], Zakosarenko V[2], van Leeuwen P[3], Schiermeier S[3], Geue D[3], Grönemeyer D[3], Hatzmann W[3], Stolz R[2], Schulz M[2], Meyer M[1], and Meyer H-G[2]

[1] Supracon AG, 07745 Jena, Germany
[2] Institute of Photonic Technology, 07745 Jena, Germany
[3] University Witten/Herdecke, Bochum, Germany

nikolai.bondarenko @ ipht-jena.de

ABSTRACT

First-order planar SQUID gradiometers were used to construct the fetal magnetocardiography (fMCG) system. Planar SQUID gradiometers were fabricated on the basis of the Nb/Al-O/Nb technology developed at IPHT Jena. Two gradiometer pickup loops with dimensions of 2 cm x 2 cm and a baseline of 4 cm were integrated on chip. The intrinsic noise corresponds to a field resolution in one loop better then 3 fT/√Hz. A second-order gradiometer was realized electronically. Three SQUID magnetometers arranged orthogonally to each other were used to improve the noise suppression. The external dimensions of the liquid helium dewar are 23 cm in diameter and 77 cm in height. For continuous work the system needs to be refilled twice a week.
During the test measurements in an unshielded hospital environment, 12 pregnant women between the 28th and 38th week of gestation were measured. Two more women with the 25th and 36th week of gestation were measured in unshielded environment of physical laboratory at IPHT. In each case data were acquired from different positions over the abdomen.
The developed fMCG system shows stable operation in medical clinic without magnetic shielding. The system allows the registration of fMCG signal with sufficient quality for subsequent heart rate analysis from at least 80% of patients.

KEYWORDS: SQUID, planar gradiometer, fetal MCG.

INTRODUCTION

Magnetic signals induced by the human body provide useful information for medical diagnostics. SQUIDs (Superconducting Quantum Interference Devices), as the most sensitive sensors to magnetic field, provide the measurements of the magnetic field produced by the human body. In this work, we will concentrate on the measurement of the fetal heart signal.

The fetal magnetocardiography is effective for study cardiac physiology in the unborn [1]. The method can be also successfully applied for diagnosing clinically relevant fetal arrhythmia [2]. The wide use of this method is restricted by the necessity of the cryogenic equipment and the presence of magnetic noise much higher then the signals to be measured. These magnetic disturbances can be reduced by the use of magnetically shielded rooms but they are very expensive.

Here we present a second version of SQUID magnetometer [3] specially designed for measurements of the fetal heart signal in magnetically unshielded environment.

METHODS

Our fMCG system is based on integrated first-order planar gradiometers. This type of gradiometers provides very high common mode rejection of magnetic noise from distance sources.

The gradiometers are manufactured in standard all-refractory Nb/Al-O/Nb technology developed at IPHT Jena. They are waterproof and robust against thermal cycling. Standard silicon 4-inch wafers are used.

The gradiometer has two pick-up loops connected in series. The main gradiometer parameters are shown in Table I. A more detailed description of the SQUID and gradiometers is given in reference [4].

Table I
Main gradiometer parameters

Parameter	Value
Chip size	6 cm × 2 cm
Size of one pick-up loop	2 cm × 2 cm
Size of Josephson junction	3.2 µm × 3.2 µm
SQUID inductance	350 pH
Pickup loop inductance	250 nH
Effective volume	300 mm^3
Effective pick-up area	7.5 mm^2
Baseline	4 cm

Typically, the gradiometer has an intrinsic noise resolution better then 2 fT/ √Hz and common mode rejection more then 5000.

The system contains three gradiometers and three magnetometers. Two gradiometers are placed on the bottom of the cryostat and aligned parallel to each other. The chips lay in a horizontal plane, so the gradient of the vertical field component B_Z along horizontal *x*-direction is measured (dB_Z/dx). They pick up the MCG signal. The third gradiometer is placed parallel to them at a height of 6 cm from the cryostat bottom. It is used as a reference to built two second-order gradiometers electronically. The second order gradiometers measure effectively the gradient ($d^2B_Z/dx{\cdot}dz$).

Three orthogonal SQUID magnetometers were used to enhance the common mode rejection of the gradiometers. To operate the SQUIDs we used FLL (flux locked loop)-electronics.

The FLL-electronics is controlled by a digital electronics operating with microcontroller model PIC 16F877. The digital electronics provides automatic and manual adjustment of the SQUID working point, switches between FLL and RESET modes of FLL-electronics and supplies test signals to the SQUID.

The gradiometers are mounted in a special fiberglass cryostat manufactured by Cryoton Ltd.[5] The cryostat has a volume of 7.6 l and for continuous work needs to be refilled twice a week. The cryostat has a flat bottom, the warm to cold distance is 16 mm and the external dimensions are 23 cm in diameter and 77 cm in height.

The data acquisition system is made by IPHT Jena e.V. The signals from FLL-electronics are amplified, low-pass filtered, and digitized with a resolution of 24 Bit and a sample rate of 1000 samples/s. These samples are packed in packages by a FPGA and send to a PC via optical network connection.

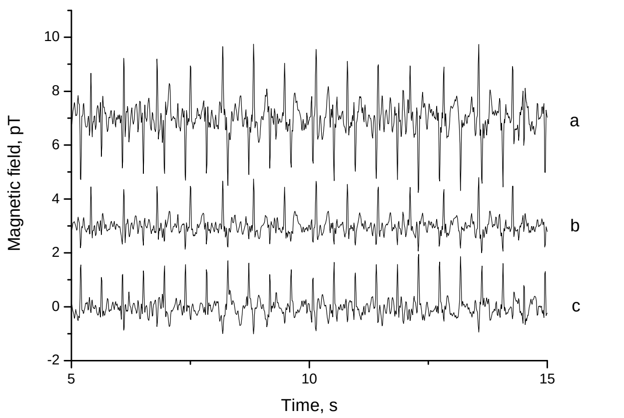

Fig.1 Real time fMCG measured in an unshielded hospital environment. The curve 'a' ($2{\times}G2\text{-}G1\text{-}G_{ref}$) contains mother and fetal signals. The curve 'b' ($G2\text{-}G_{ref}$) contains mainly signal of mother. The curve 'c' (G1-G2) contains only fetal signal). The age of fetus is 36 weeks.

Before the test measurements the system was characterized in large Helmholz coils having homogeneity better then 10^{-5} in 10 cm cube in the coils centre. The response of each gradiometer to the homogeneous magnetic field was measured. These data can be used for the electronic compensation of the parasitic areas of the gradiometers. The second opportunity that provides the system is to use the least squares algorithm [6]. For the proper work of least squares algorithm the main components of 50 Hz noise are filtered before the use of the algorithm.

The implemented configuration of the system allows filtering out of the disturbances introduced by mother's heart. It can be done during the measurements by proper orientation of the dewar with the gradiometers with respect to the mother's heart [3] or during data processing - using different combinations of signal and reference gradiometers (Fig.1).

RESULTS

Test measurements were made in unshielded environment of university hospital in Witten and in the laboratory of IPHT Jena. 14 pregnant women between the 25th and 38th week of gestation were measured. In each subject, data were acquired from different positions over the abdomen. The duration of each measurement was > 2 minutes. Stable fMCG signals were obtained during 2 minutes of measurement with signal-to-noise ratios of 3 to 5 in more then half of the subjects. Unstable signals (signal-to-noise ratios of 1 to 2) were present in 3 subjects. In the remainder, measurements were unsuccessful. All data from unsuccessful measurements contained strong interfering signals in the frequency range of respiration. This suggests that the source of disturbances was in the clothes of patients and during the routine measurements, the results could be improved by demagnetization and/or the use of appropriate dress.

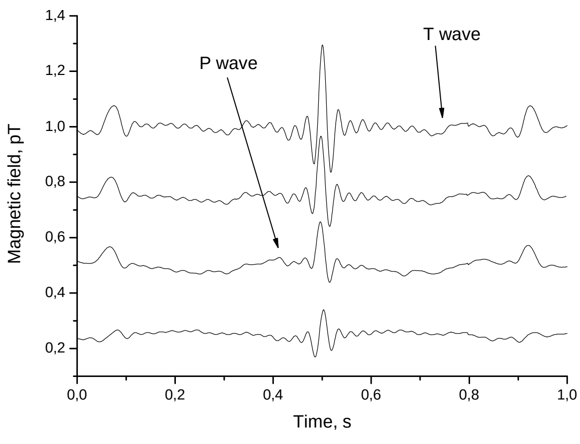

Fig.2. Averaged QRS complex of a fetus in the 28th week of gestation.

Figure 1 shows a real-time fMCG signal obtained by the developed fMCG system. The data were passed through digital band pass filter at 1.0-40 Hz and notch filters.

Although the first main goal of a clinically viable fMCG system would be to determine the fetal heart rate and its variability, the signals may also be averaged in order to permit the examination of the de- and repolarization waves of the fetal beat. Figure 2 shows an averaged signal of a fetus in the 28th week in which the P wave, RS complex and T wave are clearly recognizable. The ringing around the QRS complex is due to the online filtering of the signal and can be avoided using appropriate signal processing.

An example of R-R interval diagram is presented in Figure 3.

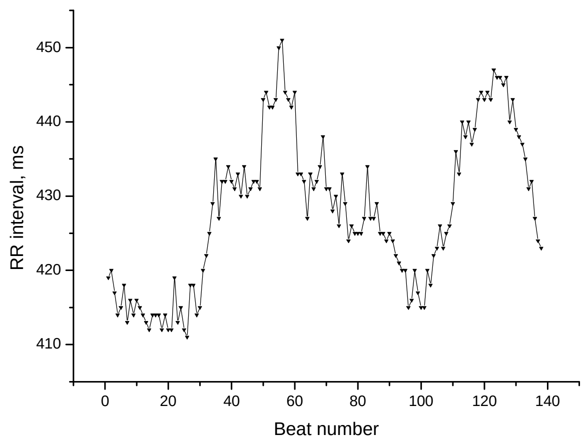

Fig 3. Example of the R-R interval diagram. The age of fetus is 28 weeks.

CONCLUSION

This work demonstrates that the developed fMCG system shows stable operation in medical clinic without magnetic shielding. The system allows the registration of fMCG signal with sufficient quality for subsequent heart rate analysis from at least 80% of patients.

ACKNOWLEDGEMENT

The authors would like to acknowledge A.Krüger, T.Krause and F.Bauer who were involved in the development of the system at IPHT Jena. This work is supported by Federal Ministry of Economics and Technology of Germany, grant Nr.061066.

REFERENCES

[1] Grimm B, Haueeisen J, Huotilainen M, et al. (2003) Recommended standarts for fetal magnetocardiography. *Pacing Clin. Electrophysiol. 26*: 2121-2126.

[2] Van Leeuven P, Hailer B, Bader W, Geissler J, Trowitzsch E, Grönemeyer DH (1999) Magnetocardiography in the diagnosis of fetal Arrhytmia. *Br J Obstet Gynaecol 106*: 1200-1208.

[3] Stolz R, Bondarenko N, Zakosarenko V, Schulz M and Meyer H-G (2003) Integrated gradiometer-SQUID system for fetal magneto-cardiography without magnetic shielding. *Supercond Sci Technol* 16: 1523-1527.

[4] Stolz R, Fritzsch L, and Meyer H-G (1999) LTS SQUID sensor with a new configuration. *Supercond Sci Technol* 12: 806-808.

[5] http://www.cryoton.webzone.ru

[6] Haykin S (1991) adaptive Filter theory 2nd edn (Englewood Cliffs, NJ: prentice-Hall).