Multichannel fetal magnetocardiography using SQUID bootstrap circuit*

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Fetal magnetocardiography (MCG) is a sophisticated non-invasive technique for the fetal heart diagnosis. We constructed a multichannel fetal MCG system based on a novel superconducting quantum interference device (SQUID) direct readout scheme called SQUID bootstrap circuit (SBC). The system incorporates four SBC gradiometers for the signal detection and three SBC magnetometers as the references. The fetal MCG signal at a 28-weeks' gestation was measured. By the fetal MCG signal separation and average, the P-wave and QRS complex can be clearly identified. These results indicate that the SBC is one of the most promising techniques for the fetal MCG recordings.

Keywords: SQUID, gradiometer, fetal magnetocardiography

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1. Introduction

Fetal magnetocardiography (MCG) is a non-invasive method to record and analyze the magnetic field generated by the electrical activity of a fetal heart. It shows the typical features of an adult electrocardiography (ECG), e.g., P-wave, QRS-complex, and T-wave. Since the first record in 1974,[1] fetal MCG has been demonstrated to be very helpful for the detection and classification of arrhythmias and the study of congenital heart diseases.[2–4]

The fetal MCG signal is extremely weak and normally measured by using low-T_c superconducting quantum interference devices (SQUIDs). In order not to degrade the SQUID sensitivity, the output voltage of the SQUID must be measured with a very low noise. Traditionally, ac flux modulation, matching transformer, and phase-sensitive detection are used. However, these will increase the system complexity. To simplify the SQUID readout electronics, several direct readout schemes have been introduced, e.g., additional positive feedback (APF),[5] noise cancelation (NC),[6] double relaxation oscillation SQUID (DROS),[7] and SQUID bootstrap circuit (SBC).[8] These schemes provide large flux-to-voltage transfer coefficients ($\partial V/\partial \Phi$) without flux modulation, which are well suited for multichannel SQUID systems. Besides high sensitive SQUID and readout schemes, successful implementation of the fetal MCG measurements requires high-performance cancellation methods to suppress the very strong environmental noises. Up to now, based on different SQUID gradiometer techniques, many multichannel fetal MCG systems have been developed and used for the clinical studies.[9]

As a novel voltage-biased SQUID direct readout scheme, the performance of SBC has been demonstrated to be better than either APF or NC schemes.[10] In our previous studies, we reported on a niobium SQUID gradiometer module with the SBC scheme.[11] Using the above gradiometer module, biomagnetic signals were successfully carried out within a magnetically shielded room (MSR).

In this paper, we describe an SBC-based multichannel fetal MCG measurement, including the system design considerations, system setup, experimental results, and the data processing.

2. System setup

In our work, the gradiometer was used to pick up the fetal MCG signal and suppress the environmental noise. It was fabricated by connecting a first-order axial gradient pickup coil to an SBC chip, as shown in Fig. 1(a). The pick-up coil was made by winding a superconducting niobium wire on a ceramic support. The diameter of the niobium wire is 0.1 mm. The pickup coil has a configuration of 1–1 turns with a baseline of 100 mm and diameter of 18 mm. To avoid the field dis-

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tortions around the gradiometer module, the superconducting shielding tube was not used. Besides the gradiometer, SBC magnetometer was used as reference to further improve the balancing of the gradiometer. The encapsulated magnetometer is shown in Fig. 1(b). The magnetic field sensitivity was calibrated to be about 8.1 fT/Hz$^{1/2}$. Detailed description and calibration of the SBC gradiometer and magnetometer chips is given in Refs. [10] and [11].

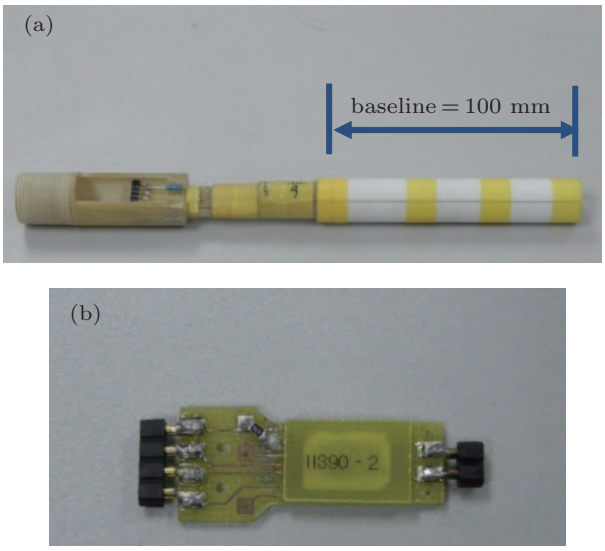


Fig. 1. (color online) Photographs of the fabricated SBC (a) gradiometer module and (b) encapsulated SQUID magnetometer.

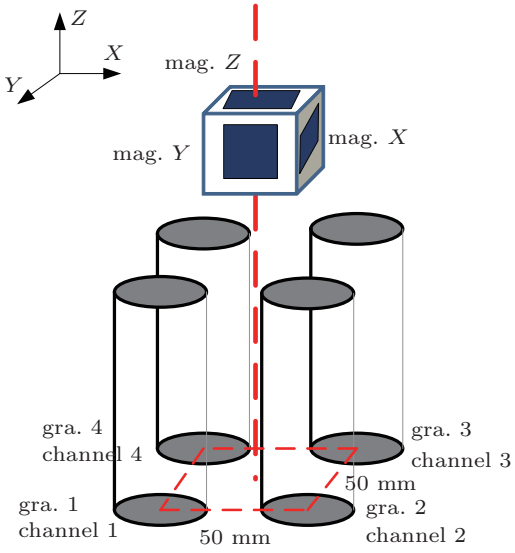


Fig. 2. (color online) Arrangement of the gradiometers and magnetometers.

In our multichannel fetal MCG system, there are four SBC gradiometers and three reference SBC magnetometers. They were placed on a nonmagnetic cryostat. The four pickup coils were located on the four corners of a 50 mm×50 mm square. The distance between the lowest pickup loop and the outer cryostat bottom is only 16 mm for maximizing signal detection. The voltage to magnetic field transfer coefficients of the four channels equivalent to the pickup loop were calibrated to be 1.521 pT/mV, 1.600 pT/mV, 1.600 pT/mV, and 1.505 pT/mV respectively. Figure 2 shows the arrangement of the gradiometers and magnetometers. The reference magnetometers were fixed orthogonally to a fiberglass cube. The size of the cube is 10 mm×10 mm×10 mm.

All the fetal MCG measurements were carried out within an MSR. The SBC outputs were digitalized by a 24-bit A/D card (NI PCI-4472) at a sample rate of 1 kHz. The data were stored for further processing. High frequency noise, low frequency drifts, maternal MCG, and other artifacts were removed by a combination of digital low-pass FIR filter with a cutoff frequency of 90 Hz, reference compensation with a smoothing least-square (LS) algorithm and fixed-point independent component analysis (FastICA) algorithm respectively.[12–16] Afterwards, the fetal MCG data were averaged to obtain a higher signal-to-noise ratio (SNR).

3. Results of the fetal MCG measurements

Because the fetal MCG signal is extremely weak, the pickup coil needs to be closer to the fetal heart during the measurements. Therefore, a fetus-voice meter was used to preliminary locate the fetal heart. Afterwards, the SBC gradiometer was placed just over the maternal abandon around the fetal heart by tilting the helium cryostat of about 30 degrees away from the vertical direction. Figure 3 shows the measured four-channel fetal MCG traces. The pregnant subject was at a 28-weeks' gestation. From the recorded traces of channels 3 and 4, both the fetal heart signals and maternal heart signals were clearly measured. Comparing to the maternal heart rate, the fetus's was much higher with about 150 beats per minute. The QRS peak of the fetal MCG in channel 4 was about 2 pT. However, for channels 1 and 2, only the maternal MCG signals can be clearly identified. The reason of the measuring differences was preliminary analyzed. The longer baseline of the pickup coil with 100 mm is very helpful for the detection of the far away maternal heart source.[17] As a result, the maternal MCG signal can be clearly recorded from all the four channels. Comparing with the maternal heart, the size of the fetal heart is smaller and the amplitude of the fetal MCG signal is much weaker. The fetal MCG signal decreases rapidly with the increase of detection distance. Attribute to the shorter distance between the pickup coils and the position of the fetal heart, the fetal MCG signals were clearly detected in channels 3 and 4.

As shown in Fig. 3, the fetal and maternal MCG signals were overlapped together in the time traces. To further suppress the residual noise, the FastICA algorithm was adopted to separate the fetal MCG signal. Figure 4 shows the separated

sources from the above original recordings. The fetal and maternal MCG sources were totally separated. Besides the fetal and maternal MCG sources, the residual sources were low frequency drift and the random noise. The low frequency drift mainly comes from the maternal breath. The residual noise of the separated fetal MCG source may be attributed to the limitation of the measuring channels with only four and the lower signal-to-noise ratio (SNR) of the measured traces.[18] Based on the separated fetal MCG source, the fetal MCG signals can be retrieved.

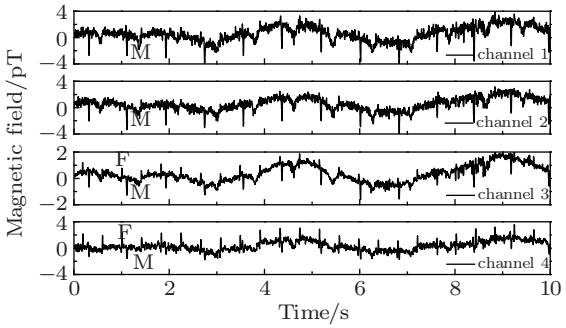


Fig. 3. Fetal MCG measurements of a fetus at a 28-weeks' gestation.

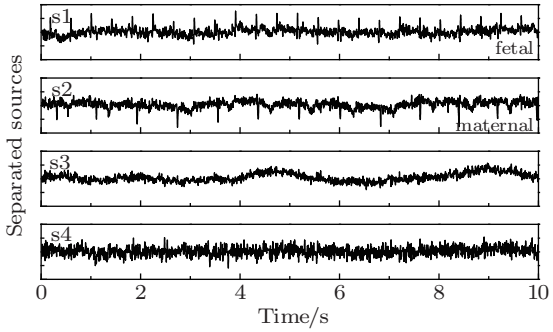


Fig. 4. Fetal MCG source separations by the FastICA algorithm.

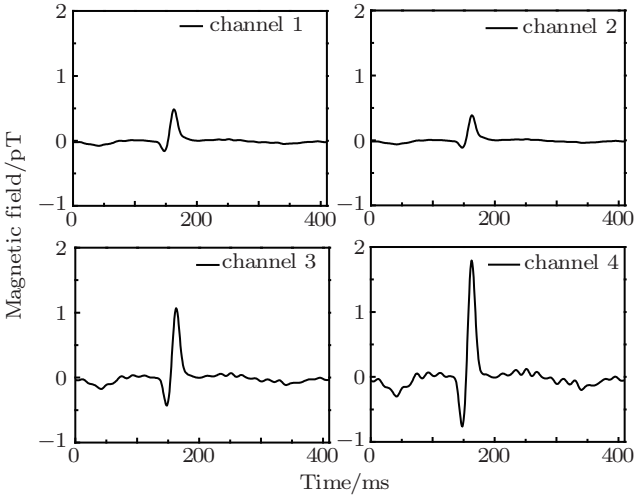


Fig. 5. Four-channel averaged fetal MCG signals.

In order to improve the SNR of the fetal MCG signals, the multi-cycle fetal MCG signals were averaged based on the R peaks and intervals of R–R peaks. Figure 5 shows the averaged fetal MCG signals. The P-wave and QRS complex were clearly detected by all the four channels. The SNR of the fetal MCG signals was sufficient to perform the fetal heart clinical diagnosis.

4. Conclusion and outlook

In conclusion, we have presented a multichannel SBC system for the fetal MCG measurements. The system consists of four SBC gradiometers and three orthogonal reference SBC magnetometers. With the system set up in an MSR, the fetal MCG signal from the 28th week gestation was successfully recorded.

Due to the smaller area of the fetal heart, the distance between the pickup coils should be shorter. In addition, the number of system channels was not enough for the fetal MCG recordings. Therefore, we plan to construct an optimized fetal MCG system with more channels in the near future.

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References

[1] Kariniemi V, Ahopelto J, Karp P J and Katila T E 1974 *J. Perinat. Med.* **2** 214
[2] van Leeuwen P, Hailer B, Bader W, Geissler J, Trowitzsch E and Grönemeyer D H 1999 *Br. J. Obstet. Gynaecol.* **106** 1200
[3] Kähler C, Grimm B, Schleussner E, Schneider A, Schneider U, Nowak H, Vogt L and Seewald H J 2001 *Prenat. Diagn.* **21** 176
[4] Janette F S, Bageshree C and Ronald T W 2008 *Heart Rhythm* **5** 1073
[5] Drung D, Cantor R, Peters M, Scheer H J and Koch H 1990 *Appl. Phys. Lett.* **57** 406
[6] Kiviranta M and Seppä H 1995 *IEEE Trans. Appl. Supercond.* **5** 2146
[7] Lee Y H, Kim J M, Kim K, Kwon H, Yu K K, Kim I S and Park Y K 2006 *Supercond. Sci. Technol.* **19** S284
[8] Xie X M, Zhang Y, Wang H W, Wang Y L, Mück M, Dong H, Krause H J, Braginski A I, Offenhäusser A and Jiang M H 2010 *Supercond. Sci. Technol.* **23** 065016
[9] Pizzella V, Penna S D, Gratta C D and Romani G L 2001 *Supercond. Sci. Technol.* **14** R79
[10] Zhang G F, Zhang Y, Dong H, Krause H J, Xie X M, Braginski A I, Offenhäusser A and Jiang M H 2012 *Supercond. Sci. Technol.* **25** 015006
[11] Zhang G F, Zhang Y, Zhang S L, Krause H J, Wang Y L, Liu C, Zeng J, Qiu Y, Kong X Y, Dong H, Xie X M, Offenhäusser A and JiangM H 2012 *Physica C* **480** 10
[12] Zhang S L, Wang Y L, Wang H W, Jiang S Q and Xie X M 2009 *Phys. Med. Biol.* **54** 4793
[13] Liu D T, Tian Y, Ren Y F, Yu H W, Zhang L H, Yang Q S and Chen G H 2008 *Chin. Phys. Lett.* **25** 2714
[14] Li Z, Chen G H, Zhang L H, Yang Q S and Feng J 2005 *Chin. Phys.* **14** 1095
[15] Hyvärinen A and Oja E 1997 *Neural Computation* **9** 1483
[16] Comani S, Mantini D, Alleva G, Luzio S D and Romani G L 2004 *Physiol. Meas.* **25** 1459
[17] Zhang Y, Wolters N, Lormparski D, Zander W, Banzet M, Schubert J, Krause H J, Geue D and van Leeuwen P 2006 *Supercond. Sci. Technol.* **19** S266
[18] Zhang S L, Liu M, Zeng J, Wang Y L, Kong X Y and Xie X M 2012 *IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI* 2012), January 5–7, 2012, Hong Kong, China, p. 253