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Unshielded fetal magnetocardiography system using two-dimensional gradiometers

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We developed a fetal magnetocardiography (fMCG) system that uses a pair of two-dimensional gradiometers to achieve high signal-to-noise ratio. The gradiometer, which is based on a low-T_c superconducting quantum interference device, detects the gradient of a magnetic field in two orthogonal directions. Gradiometer position is easy to adjust by operating the gantry to drive the cryostat in both the swinging and axial directions. As a result, a fMCG waveform for 25 weeks' gestation was measured under an unshielded environment in real time. Moreover, the *P* and *T* waves for 25 and 34 weeks' gestation, respectively, were obtained by averaging. These results indicate that this two-dimensional gradiometer is one of the most promising techniques for measuring fetal heart rate and diagnosing fetal arrhythmia. © *2008 American Institute of Physics.*
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The fetal magnetocardiography (fMCG), which was first recorded in 1974,[1] is effective for diagnosing fetal heart disease because it provides fetal cardiac electrophysiologic data. Moreover, it is not affected by air or body tissue (which have permeability of almost $\mu_0 = 4\pi \times 10^{-7}$), while the vernix caseosa (which has poor conductivity) attenuates the intensity of the fetal electrocardiography. Moreover, a fMCG can be obtained in a noninvasive and contactless manner. In reflection of these merits, many studies supporting the efficacy of fMCG have been reported.[2–5] On the other hand, because of its large scale, installing a fMCG system is still a major obstacle for a hospital.

To overcome the obstacle, a few studies on fMCG measurements in an unshielded environment have been reported.[6] However, it is still difficult to measure fMCG of a fetus at earlier than 30 weeks' gestation without shielding. Other techniques are thus necessary to overcome these difficulties. Recently, we proposed the concept of a "two-dimensional gradiometer," which we expected to be effective for biomagnetic measurements in an unshielded environment.[7] In the present study, we were aiming at developing a fMCG system using two-dimensional gradiometers and measuring the fMCG signal in an unshielded environment.

Figure 1 shows a photograph of our developed fMCG system. The gradiometers are installed at the bottom of the cryostat, and the gradiometer position can be easily adjusted by driving the gantry in both the swinging and axial directions using a hydraulic control system. The size of the gantry is 1.2 m wide, 1.0 m deep, and 2.1 m high. The installation area of the total fMCG system including the bed and other electronic equipment is therefore about one-third that of a conventional MCG system with a magnetically shielded room.

Figure 2 schematically shows the configuration of the fMCG system. In this study, a pair of two-dimensional gradiometers based on a low-T_c superconducting quantum interference device (SQUID) was used to measure a fMCG signal less than a few picotesla in an unshielded hospital environment. The low-T_c SQUIDs are conventional Ketchen-type dc varieties made of Nb/Al–AlO_x/Nb. In addition, they are cooled by liquid helium in a cryostat and operated by a direct-coupled flux-locked-loop (FLL) circuit fixed to the cryostat. The distance between the lowest pickup loop and

FIG. 1. (Color) Photograph of the fMCG system.

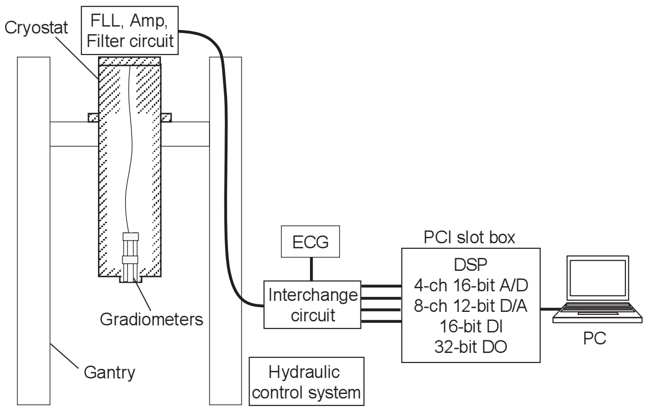

FIG. 2. Schematic diagram of the fMCG system.

the outer bottom surface of the cryostat is 9 mm to achieve high signal intensity. The cryostat is coated by conductive material to shield high-frequency electromagnetic fields which degrade SQUID performances. Evaporation rate of liquid helium is 1.8 l/day, so additional supply is required once every two weeks. After being amplified and filtered by the analog circuit, the FLL outputs are converted to digital signals and processed by a digital signal processor in real time.

The two-dimensional gradiometer is described in detail here. Figure 3(a) shows the two developed two-dimensional gradiometers. Each gradiometer detects the gradient of a magnetic field in two orthogonal directions, i.e., the axial-second-order gradient and planar-first-order gradient of the magnetic field, as shown in Fig. 3(b). The total flux through the pickup coil Φ_p is thus

$$\Phi_p = (\Phi_{0a} - 2\Phi_{1a} + \Phi_{2a}) - (\Phi_{0b} - 2\Phi_{1b} + \Phi_{2b}), \qquad (1)$$

where Φ_{0a}, Φ_{1a}, Φ_{2a}, Φ_{0b}, Φ_{1b}, and Φ_{2b} are the flux through each pickup loop, as shown in Fig. 3(b).

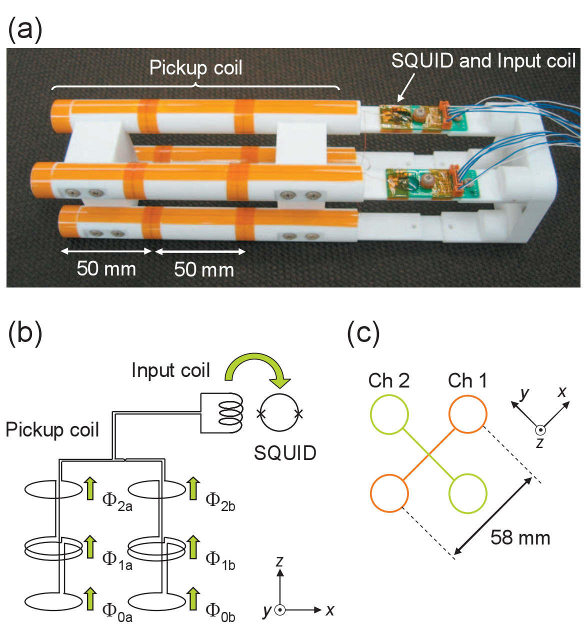

FIG. 3. (Color) (a) Photograph of a two-dimensional gradiometer. (b) Schematic of the pickup coil for the two-dimensional gradiometer, input coil, and SQUID. (c) Planar arrangements of a pair of pickup coils.

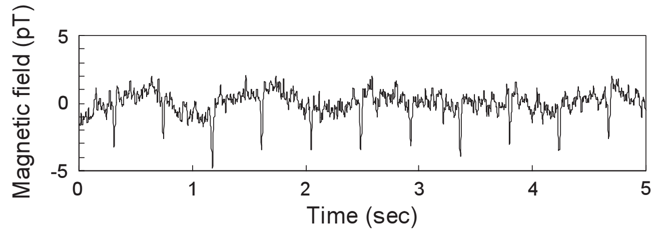

FIG. 4. Real-time fMCG waveforms of fetus at 25 weeks' gestation. The depth of the fetal heart was 30 mm.

The axial and planar baselines are 50 and 58 mm, respectively, and the pickup loop is 18 mm in diameter. The planar arrangements of the two pickup coils are perpendicular to each other, as shown in Fig. 3(c). The sensitivity of the gradiometers is 53 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$, and the noise-reduction ratio of the pickup coil is 50–60 dB.

Prior to performing the fMCG measurement, to identify the nearest position on the maternal abdominal wall from the fetal heart, we measured depth (distance between the fetal heart and maternal abdominal wall) and size (diameter) of the fetal heart by ultrasonography. The pickup coils were then simply brought close to that position by operating the control panel on the gantry. Measurement time was usually 3 min.

Figure 4 shows a real-time fMCG waveform obtained by the developed fMCG system. The pregnant subject was at 25 weeks' gestation, and the depth of the fetal heart was 30 mm. The data were passed through bandpass filtering at 1.0–30 Hz and notch filtering. The QRS peaks of the fMCG signal were measured clearly. In the figure, the maternal MCG was not identified because the gradiometer was far enough from the mother's heart. Fetal heart rate was also obtained in real time by measuring the *R-R* interval.

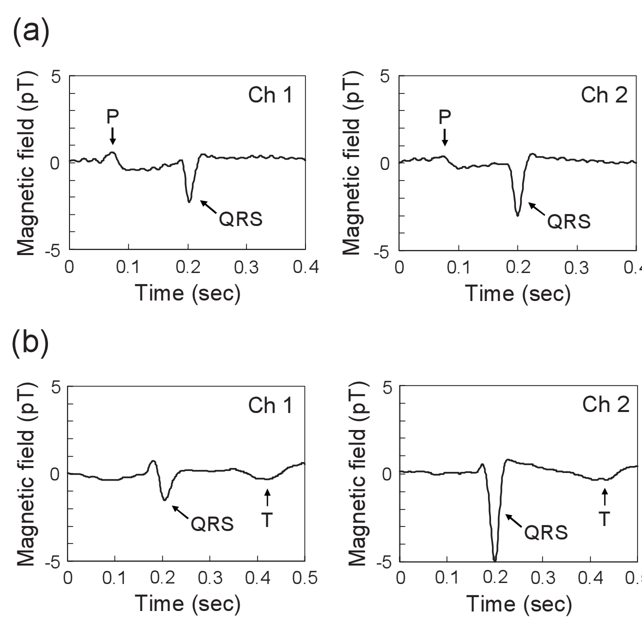

FIG. 5. (a) Averaged fMCG waveforms of a fetus at 25 weeks' gestation. The depth of the fetal heart was 30 mm. Averaging number was 329 readings. The *P* wave is clearly detected. (b) Averaged fMCG waveforms for 34 weeks' gestation. The depth of the fetal heart was 52 mm. Averaging number was 298 readings. The *T* wave is clearly detected.

Figure 5(a) shows averaged fMCG waveforms obtained from the same subject described above (averaged over 329 readings). As shown in the figure, the *P* wave was clearly detected by both gradiomters. Figure 5(b) shows averaged fMCG waveforms obtained from another subject, at 34 weeks' gestation, where the depth of the fetal heart was 52 mm (averaged over 298 readings). According to this figure, the *T* wave was clearly detected by both gradiometers.

In Fig. 3(c), the magnetic field generated by a current parallel to the *x*-direction is mainly detected by the channel-one pickup coil, while the channel-two pickup coil mainly detects the magnetic field generated by a source current in the *y*-direction. Accordingly, this configuration makes it possible to detect a magnetic field produced by a source current in any direction perpendicular to the *z* axis. Moreover, the direction of the fetal myocardial ion current can be estimated by using current arrow vector $\boldsymbol{I}$, which is given by the following simple equation:[8]

$$\boldsymbol{I} \sim \left(\frac{\Delta B_z}{\Delta y}, - \frac{\Delta B_z}{\Delta x} \right) \propto (\Phi_{\mathrm{ch2}}, - \Phi_{\mathrm{ch1}}), \tag{2}$$

where Φ_{ch1} and Φ_{ch2} are the total fluxes through the pickup coils of channels 1 and 2, respectively, as shown in Eq. (1).

In conclusion, the experimental results presented above demonstrate that the developed fMCG system using a pair of two-dimensional gradiometers can measure not only fetal heart rate but also basic MCG time parameters, such as PQ interval, QRS width, and QT interval,[9] in an unshielded hospital environment.

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