AIP | Review of Scientific Instruments

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Citation: Review of Scientific Instruments **70**, 4702 (1999); doi: 10.1063/1.1150133
View online: http://dx.doi.org/10.1063/1.1150133
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/70/12?ver=pdfcov
Published by the AIP Publishing

A vector fetal magnetocardiogram system with high sensitivity

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(Received 20 April 1999; accepted for publication 15 September 1999)

The vector fetal magnetocardiogram (V-FMCG) system that measures the three orthogonal components of the magnetic field from a fetal heart has been developed to clearly observe fetal cardiac activity during pregnancy by using the superconducting quantum interference device. To detect a clear V-FMCG signal, the bottom of the cryostat was made of thin glass–fiber-reinforced plastic and the total length between the pickup coil to the outer surface is 12 mm. Because the cryostat bottom was made thinner, the area of the cryostat's top and bottom could be made smaller, thus a low evaporation loss (<1.2 l per day) and a long refilling interval (>10 days) were obtained. The gantry was able to tilt the cryostat and the bed could move in three axis directions, which made it possible to easily locate the vector pickup coil at an optimum position to obtain the maximum magnetic field from a fetal heart. We obtained V-FMCGs from 21 normal fetuses with gestation periods of 27–38 weeks. Using these vector signals, the dipoles were estimated and the relationship between the strength of the dipole moments and the number of gestation weeks could be obtained. Thus, V-FMCG seems to represent a new noninvasive tool for clearly detecting the electrophysiological activity of a fetal heart.
[S0034-6748(99)04612-2]

I. INTRODUCTION

Fetal magnetocardiogram (FMCG) signals, which are produced by an ion current in the cardiac muscle of a fetal heart, were first clearly detected in the 1970's.[1,2] Since then, a general method of measuring the normal component of a FMCG signal has been used because the influence of the volume current is less than that of the tangential component. However, we have demonstrated the potential of using FMCG for clinical application by measuring the tangential component of an adult magnetocardiogram (MCG).[3,4] These studies suggested that the tangential component of biomagnetic data was important for detection of not only adult, but also fetal MCG signals. When obtaining both negative and positive peaks of the normal component to estimate a dipole, though, the sensing area of the cryostat has had to be quite large, so the cryostat bottom must be made of a thick wall to avoid bending due to the strength of the vacuum. Therefore, a pickup coil in the cryostat could not be placed close to the fetal heart.

We have been investigating the application of FMCGs by using a nine-channel superconducting quantum interference device (SQUID) system with pickup coils to detect the normal component. From our measured data, the strength of the dipole moments of fetuses with gestation periods above 21 week was estimated and the magnitude of the FMCG signal for each week of gestation was calculated.[5] We found that to obtain the FMCG signal clearly, the distance between a pickup coil and the fetal heart should be shortened because the magnitude of the FMCG signals was small due to the limited sensitivity of the SQUID sensor. To reduce this distance, we made the bottom of the cryostat thinner by constructing it of glass–fiber-reinforced plastic (GFRP) with small area. However, the obtainable FMCG information was still limited because of the small sensing area. To overcome this, we have used a vector FMCG (V-FMCG), which enables us to obtain three components of a biomagnetic field. Furthermore, one dipole can be estimated by using the vector component of a FMCG signal. This article is the first report we know of on the potential of V-FMCG measurement.

II. SIMULATION OF A VECTOR FETAL MAGNETOCARDIOGRAM

The distribution of a magnetic field can be calculated by using a one-dipole-model formula of a half-infinite space.[6] In Fig. 1, contour maps of x and y components [$Bxy = \sqrt{(Bx^2+By^2)}$], and of the z component (Bz) of the magnetic field are shown along with the magnitude of the magnetic-field vector [$Bxyz = \sqrt{(Bx^2+By^2+Bz^2)}$]. In this calculation, the distance from a pickup coil to one dipole was 80 mm, and the dipole moment was (0, 250, 0) (nA m), which is the average value for 30 weeks of gestation.[5] If the limit of the FMCG peak detection is 1 pT, the detectable

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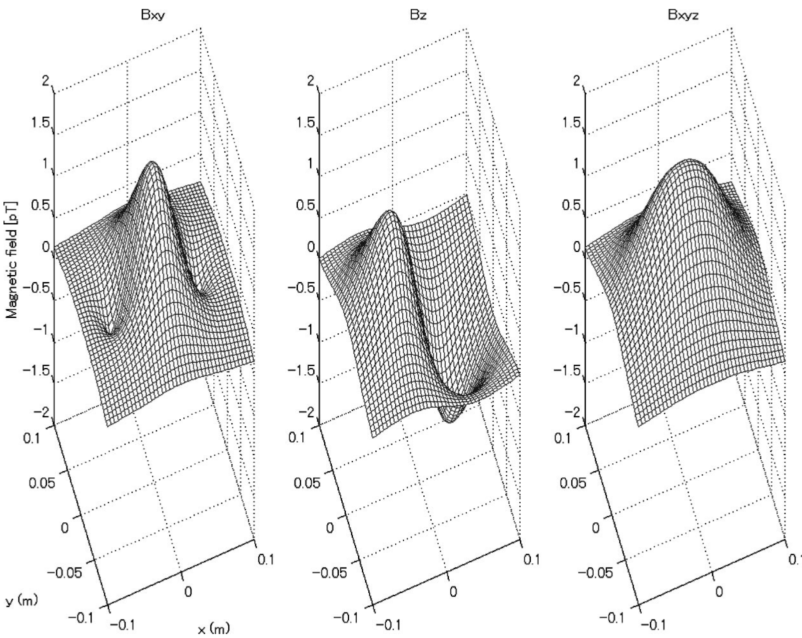

FIG. 1. Simulated magnetic-field distribution generated in a half-infinite space model by a single dipole. The dipole position was (0, 0, −80) (mm), and the dipole moment was (0, 250, 0) (nA m).

magnetic field is as shown in Fig. 2. In this case, the *Bxy* contour map of the conventional method is above the dipole, but the *Bz* contour map has a peak that is not above the dipole. The detection area of the *Bxyz* contour map combines both the *Bxy* and *Bz* signal, and the weak magnetic field from a fetal heart can be observed over a wide area. (In Fig. 2, the FMCG signal can be detected within a 50 mm radius.) These results confirmed that through measurement of the vector FMCG signal, we can easily detect an *R* wave in a smalll sensing area.

III. SYSTEM CONFIGURATION

Figure 3 shows the sensor array of vector gradiometers that contains *x*-, *y*-, and *z*-axis pickup coils. The gradiometers had a 60 mm base line. The *z*-component pickup coils were 20 mm in diameter, and the pickup coils for the *x* and *y* components were 20 mm×16 mm to equal to the sensing area of the *z*-axis pickup coil. We used a 2×2 sensor array with a sensor pitch of 30 mm. The readout electronics of these SQUID sensors were based on a flux locked loop (FLL) circuit made with a direct offset integration technique and an additional positive feedback circuit. The FLL unit was located outside of the magnetically shielded room (MSR).

Figure 4 shows a photograph of the constructed cryostat and gantry at the Tsukuba University. To enable quick adjustment of the SQUID sensor position and to obtain maximum strength V-FMCG signals over the maternal abdomen, the adjusting mechanism allows tilting at an arbitrary angle up to 30° in any direction since the cryostat installed in the SQUID sensor is mounted on a gantry. To position the subject, a bed made of nonmagnetic metals can be moved in

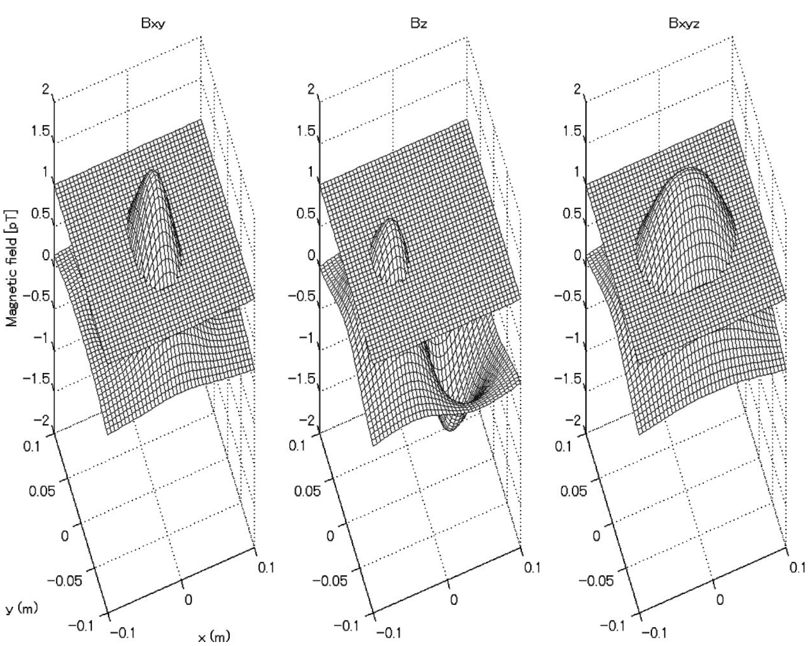

FIG. 2. Detectable magnetic-field distribution at 1 pT (as in Fig. 1).

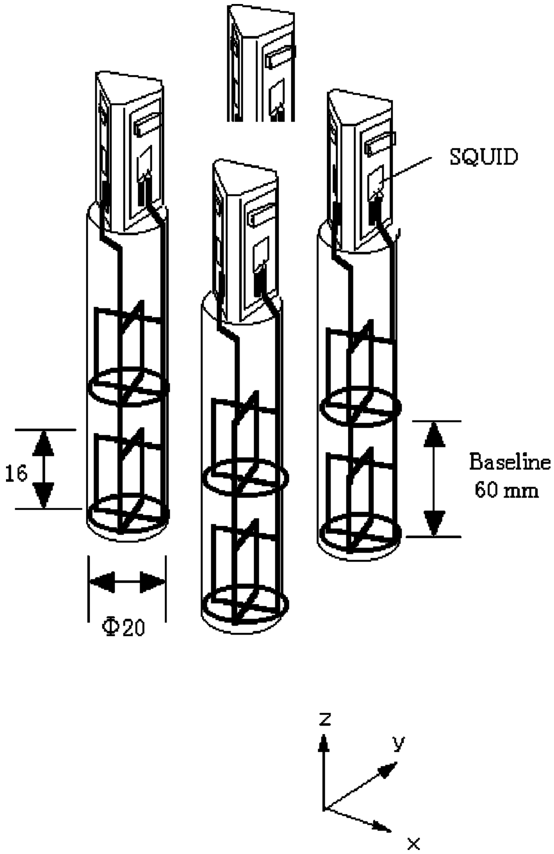

FIG. 3. Structure of the vector gradiometer array.

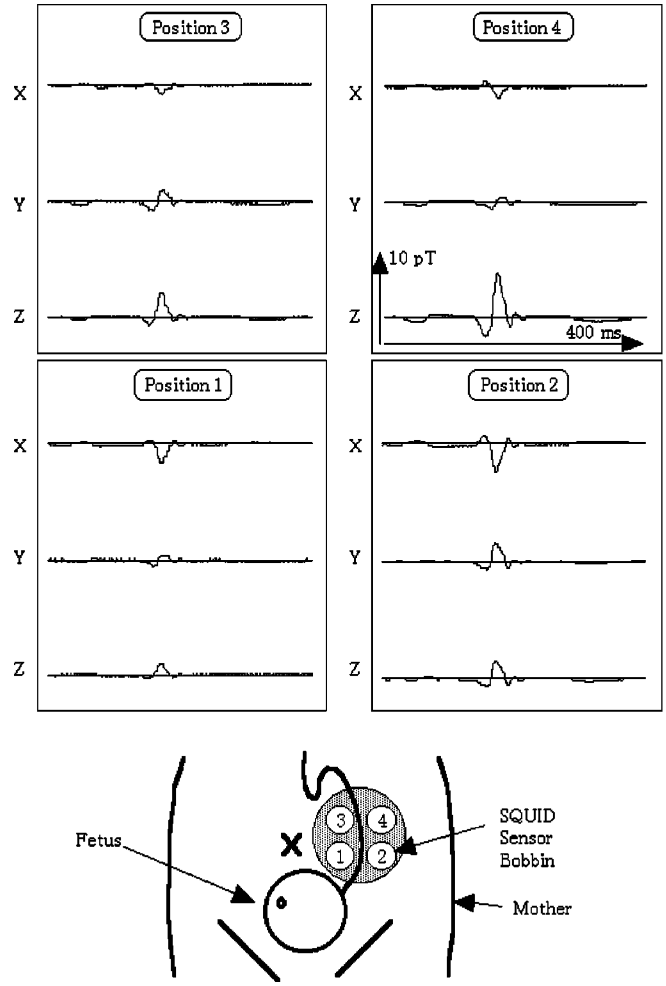

FIG. 5. Typical V-FMCG wave form. The fetus has had 35 weeks of gestation and is 46 mm from the maternal abdomen surface.

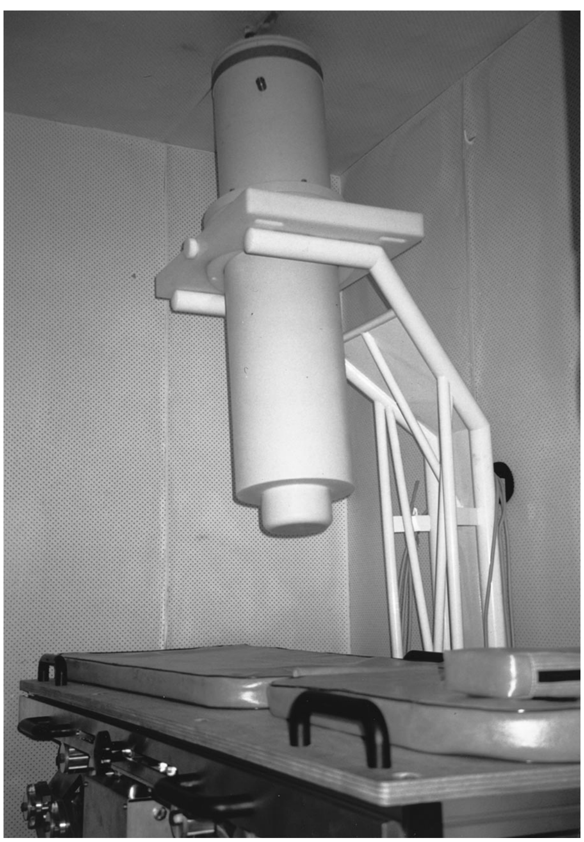

FIG. 4. Photograph of the V-FMCG system.

three directions (x,y,z) and part of the cushion on the bed can be inflated to raise part of the maternal abdomen. Furthermore, to ensure that the cryostat is set at the optimum position, a crystal-display monitor (to ensure low noise) is

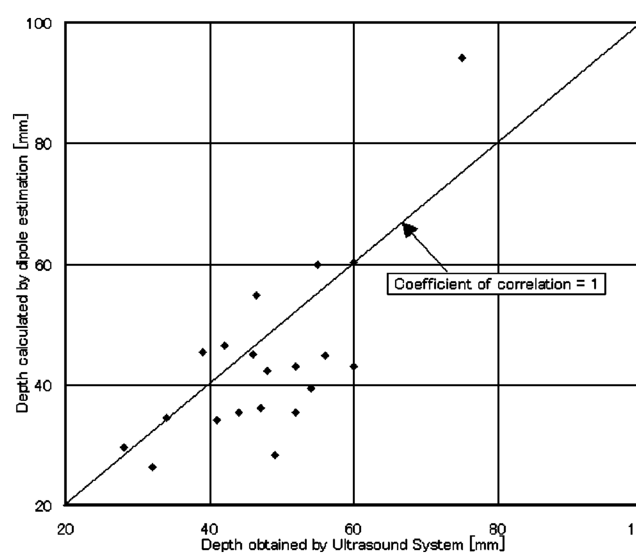

FIG. 6. Relationship between the depth obtained by ultrasound and the estimated depth.

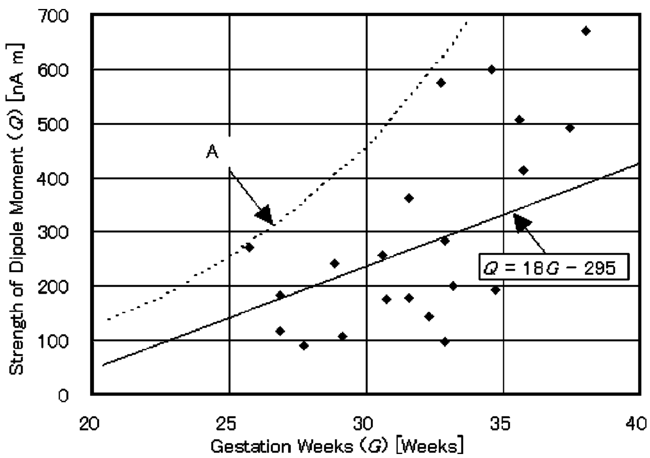

FIG. 7. Strength of the estimated dipole moment as a function of the number of gestation weeks.

installed in the MSR and the wave form of the FMCG signal is displayed. With this equipment, the FMCG signal can be detected quickly and clearly.

The cryostat bottom (from inside of the inner cylinder to the outside of the outer cylinder) is 12 mm thick. The cryostat is 1095 mm long, the outer diameter of the reserved liquid-helium section is 256 mm, and the outer diameter of the sensor part is 150 mm. The cryostat can contain 16.8 l of liquid helium to cool the sensor array, and the evaporation rate of liquid helium from the cryostat is only 1.2 l per day. Thus, the interval between the refilling of the cryostat with liquid helium is more than 10 days in general use.

IV. RESULTS AND DISCUSSION

We obtained V-FMCGs from 21 normal fetuses with gestation periods of 27–38 weeks. The average was 32 weeks. To obtain information concerning the fetal position, ultrasound measurements were performed by a medical doctor before the V-FMCG measurements. The distance from the maternal abdomen surface to the fetal heart surface ranged from 28 to 75 mm and the average depth was 48 mm.

An example of our V-FMCG results, which clearly show not only the QRS wave, but also the P and T waves, is shown in Fig. 5. The fetal body position was observed as shown in the lower figure by using ultrasound. The fetus was at 35 gestation weeks and the length bet ween the surface of the fetal heart to the maternal abdomen surface was 46 mm. The circumference of the fetal heart was 143 mm. The upper signals were calculated by a 76-times-average process as a trigger of the R-wave peak, and the maximum magnitude of the R-wave peak was about 7 pT. As mentioned (Fig. 5), we obtained an R-wave peak with the V-FMCG system that was double that obtained with the nine-channel system (an average of 4 pT compared to 2 pT). However, no weak signals other than the R wave appeared in any of the V-FMCG signals because of the orientation of the fetal heart.

The current dipole at the time of the R-wave peak can be estimated by a least-mean-squares method using a bounded homogeneous conductor model including volume–current effects if the three orthogonal components (Bx, By, Bz) of the FMCG signals are measured in a small sensing area. The 21 V-FMCG signals averaged during the time of observing all static V-FMCG signals were used to estimate one dipole of the R wave. In these estimations, to avoid a local minimum solution, the initial values of the x and y axes were set on the position with the maximum magnetic-field strength because there is a dipole under the site of the biggest vector magnetic field $(Bxyz)$ (Fig. 1). The initial depth (z axis) was fixed at 50 mm. To obtain the initial $x-y$ direction of the dipole moment, the direction was determined by averaging the exterior products of each vector magnetic field; if the vector magnetic field of positions 1, 2, 3, and 4 are $\boldsymbol{B}_1$, $\boldsymbol{B}_2$, $\boldsymbol{B}_3$, and $\boldsymbol{B}_4$, respectively, six kinds of exterior products ($\boldsymbol{B}_1 \times \boldsymbol{B}_2$, etc.) were calculated then averaged. Because this process is based on the Bio-Savar law, the dipole direction cannot be determined precisely for a volume conductor. But, this method is sufficient to obtain the dipole orientation simply.

Figure 6 shows the relationship between the depth of the estimated dipole and the depth from the maternal abdomen surface to the fetal heart surface as obtained by ultrasound. The estimated depth was calculated by subtracting the cryostat tail bottom thickness (12 mm) from the computed depth by using the above method. In Fig. 6, a line of correlation (coefficient=1) is shown as a reference line, and the correlation of our results was relatively good. Although the field components oriented parallel to the abdomen are very much effected by volume currents, the plots of Fig. 6 show little effect to determine the dipole position.

Next, we plotted the magnitude of the estimated dipole moment according to the number of gestation weeks (Fig. 7). Figure 7 also shows the average line, which was obtained by using the normal component of the magnetic field and the depth obtained by ultrasound for 35 fetuses.[5] Furthermore, the maximum line would resemble curve A in Fig. 7. Therefore, the magnitude of the measured FMCG signal might depend on the fetal orientation because only the magnetic field due to the x and y currents parallel to the sensing area appear. Although the dipole estimation contains an error in that the current distribution in the fetal heart is thought of as one current dipole, it is useful to estimate dipole strength of normal fetuses according to the number of gestation weeks for clinical use.

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