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Detection of Cardiac Hypertrophy in the Fetus by Approximation of the Current Dipole Using Magnetocardiography

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ABSTRACT

To determine the developmental changes in the myocardial current during fetal life, and to evaluate the clinical usefulness of magnetocardiography for prenatal diagnosis of cardiac hypertrophy or enlargement, we approximated the magnitude of the one-current dipole of the fetal heart using fetal magnetocardiography (fMCG). A total of 95 fetuses with gestational age of 20–40 wk were included in this study. fMCG was recorded with a nine-channel superconducting quantum interference device system in a magnetically shielded room. The magnitude of the dipole (Q) was calculated using an equation based on the fMCG amplitude obtained on the maternal abdomen and the distance between the maternal surface and fetal heart measured ultrasonographically. In uncomplicated pregnancies, the Q value correlated significantly with gestational age, reflecting an increase in the amount of myocardial current, *i.e.* myocardial mass. Moreover, the Q values in fetuses with cardiomegaly caused by various cardiovascular abnormalities tended to be higher than the normal values. Although there are some limitations of the methodology based on the half-space model, and fetal orientation may influence the magnitude of the dipole, making it smaller, fMCG recorded with a multichannel superconducting quantum interference device system is a clinically useful tool for noninvasive, prenatal, and electrical evaluation of fetal cardiac hypertrophy. **(*Pediatr Res* 50: 242–245, 2001)**

Abbreviations:
fMCG, fetal magnetocardiogram
MCG, magnetocardiogram
SQUID, superconducting quantum interference device
TCD, total cardiac dimension

Since the first clinical application of MCG for the diagnosis of fetal cardiac rhythm by Kariniemi *et al.* (1) in 1974, the magnetic field generated by the fetal heart has been measured noninvasively with satisfactory waveforms. MCG requires no pasting of electrodes to the fetal body surface and is completely noninvasive to both fetus and mother. MCG signals from the fetal heart are considered to be minimally affected by the electrical conduction properties of the tissue around the heart (2, 3). In fact, time intervals can be obtained with satisfactory signal-to-noise ratio even after the development of vernix caseosa in the second half of gestation. A number of studies, including ours, defined the developmental changes and normal ranges of various time intervals on the fMCG in uncomplicated pregnancies (4–6). However, the amplitude of the fMCG waveform has not been fully investigated (7), although it is another important variable used for the diagnosis of fetal heart diseases. One reason for this rare application is that the amplitude of fMCG measured on the maternal abdomen does not necessarily reflect the maximum value of myocardial current because of the effects of the depth and orientation of the heart. Furthermore, these biases are not easily corrected as the fetus may move during measurement.

We attempted to approximate the magnitude of the one-current dipole of the fetal heart based on the maximum value of fMCG data obtained with a multichannel SQUID system and the depth of the fetal heart determined by echocardiography in normal pregnancies. We then used these control values to assess magnitude abnormalities in fetuses with cardiomegaly resulting from excessive volume loading in cardiac ventricles. Using both data sets, we evaluated the usefulness of this technology for electrical diagnosis of cardiac hypertrophy in fetal life.

METHODS

Study population. A total of 95 fetuses with gestational age of 20–40 wk were studied. Among these, 88 had no maternal

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or fetal complications on history taking, physical examination of the mother, and fetal ultrasonography (group I) (Table 1). The other seven cases had cardiomegaly diagnosed by fetal echocardiography (group II) (Table 2). The transverse diameter of the fetal heart on the four-chamber view on echocardiography in group II ranged from 32 to 54 mm (TCD values in all seven fetuses were $>95^{th}$ percentile of the normal value) (8). The following causes of cardiomegaly were determined by fetal echocardiography: three fetuses were the recipients in twin-twin transfusion syndrome, two had arteriovenous shunt through Galen malformation, and two had endocardial cushion defect with atrioventricular regurgitation (Table 2). The study protocol was approved by the Human Ethics Review Committee of Tsukuba University School of Medicine and a signed consent form was obtained from parents before commencement of the study.

Instrumentation and measurements. fMCG was recorded using a nine-channel SQUID system, which is located in a magnetically shielded room at the University Hospital of Tsukuba. The pick-up coils were of a round-shaped, thin-film type with a diameter of 20 mm, and were allocated to nine points of a 60-mm square with a constant interval of 30 mm. The baseline distance, or the interval between the two counter-wound coils, of the first-order gradiometer was set at 60 mm. fMCG was acquired at a sampling rate of 1000 Hz in each case. A 0.1–100-Hz band-pass filter and a 50-Hz power-line noise filter were applied. Details of the SQUID system have been described in a previous report (9). Immediately before fMCG recording, the shortest distance from the maternal abdominal surface to the anterior ventricular surface of the fetal heart (d_1) was determined by ultrasonography. A view of the four cardiac chambers on fetal echocardiograms was also used to identify any structural cardiac abnormalities as well as to measure TCD. fMCG was recorded simultaneously at nine points for at least 2 min by placing the sensor array as close as possible to the maternal abdominal surface. When the maximum point was not at the center of the first mapped area and was suspected to be out of the area from the magnetic distribution pattern, the sensor array was moved a few centimeters until the peak value was detected. No less than 20 beats with the maximum amplitude and the same polarity of the waveform were selected from the tracings among nine channels. Then, signal averaging of the data triggered by the peak of the QRS complex was applied to improve the signal-to-noise ratio. According to the methods described by Williamson and Kaufman (10), the magnitude of the one-current dipole of the fetal heart was calculated, based on the data of fMCG and depth of the fetal heart, using the following equation:

$$B = \frac{0.385\mu_0}{4\pi d_1^2} Q \qquad (a)$$

where d_1 is the distance between the sensor coil and fetal ventricular wall, μ_0 is a constant of the magnetic permeability, B is the normal (z) component of the maximum magnetic force during ventricular depolarization among nine channels, and Q is the current dipole to be estimated (11). For a first-order gradiometer with baseline L (60 mm in the present system), equation (a) can be transformed into the following equation (b):

$$B = \frac{0.385\mu_0}{4\pi}\left(\frac{1}{d_1^2} - \frac{1}{d_2^2}\right) Q \qquad (b)$$

Thus,

$$Q = \frac{4\pi B}{0.385\mu_0}\left(\frac{1}{d_1^2} - \frac{1}{d_2^2}\right) \qquad (c)$$

where $d_2 = d_1 + L$.

Consequently, the magnitude of the current dipole (Q) is simply estimated using two parameters, *i.e.* the maximum magnetic force measured on the maternal abdomen (B) and the depth of the fetal heart determined by fetal echocardiography (d_1). The correlation of B and Q values with gestational age was analyzed using simple linear regression.

RESULTS

In group I, the depth (d_1, the distance from the maternal abdominal surface to the fetal ventricular wall) ranged from 22 to 75 mm (mean ± SD: 45.0 ± 10.9), and the maximum value of the surface magnetic field among nine channels (B) ranged from 1.9 to 10.8 pT (pico-Tesla). The calculated value of the estimated current dipole (Q) was 41–650 nAm (nano-Ampere · meter) (mean: 234 ± 121). These data were also stratified into four groups by gestational age, as presented in Table 1. Q values, but not B, correlated significantly with gestational age (Fig. 1).

The Q value in group II ranged from 291 to 1330 nAm. In six fetuses, the Q value was higher than the mean + 2 SD of the control for each corresponding gestational age (Table 2, Fig. 2). In particular, the Q value in the fetus with the largest heart in this study, resulting from a massive arteriovenous

Table 1. *Maximum amplitude of fMCG measured on maternal abdomen (*B*) and estimated magnitude of the current dipole (*Q*) in normal fetuses*

Gestation	*n*	d_1 (mm)*	B (pico-Tesla)	Q (nAm)
<28 wk	15	40.3 ± 7.6	2.87 ± 0.60	143 ± 58
28–31 wk	20	44.4 ± 9.3	3.42 ± 1.04	202 ± 83
32–35 wk	19	43.2 ± 11.7	4.50 ± 2.05	233 ± 110
>35 wk	32	48.1 ± 11.7	4.38 ± 1.65	297 ± 137

Values are expressed as mean ± SD.

* Depth of the fetal heart determined by fetal echocardiography.

Table 2. *Measurements of TCD and estimated magnitude of the current dipole (Q) in fetuses with cardiomegaly*

Case No.	Gestation (wk-d)	Cause of cardiomegaly	TCD (mm)	Q (nAm)
1	23-2	TTS	32	300
2	26-1	TTS	36	359
3	30-1	Galen	42	408
4	32-3	ECD	44	550
5	33-1	TTS	45	291
6	33-1	ECD	45	620
7	36-4	Galen	54	1330

TTS, twin-twin transfusion syndrome; Galen, malformation of the vein Galen; ECD, endocardial cushion defect.

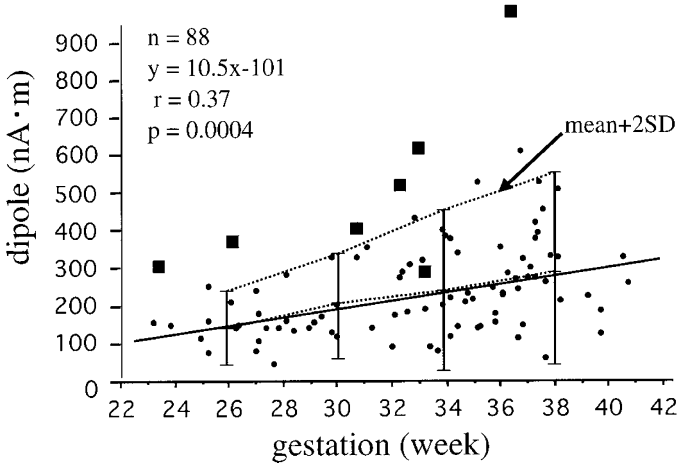

Figure 1. Composite of all 95 fMCG studies performed on normal fetuses and fetuses with cardiomegaly. The magnitude of the estimated dipole (Q) in 88 normal fetuses (*closed circles*) correlated significantly with gestational age ($r = 0.37, p = 0.0004$). In six of seven cases with cardiomegaly (*closed squares*), the Q value is larger than the mean value + 2 SD of normal fetuses.

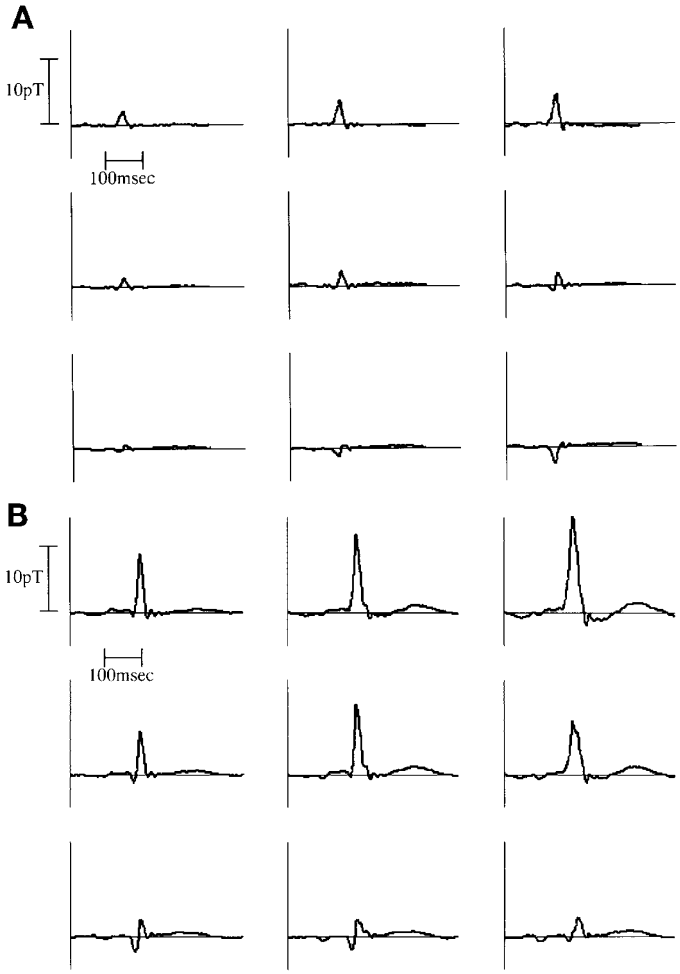

Figure 2. PQRST waveforms of fMCG after signal averaging in a normal fetus with gestational age of 36 wk (*A*) and in a fetus with marked cardiomegaly resulting from Galen malformation with gestational age of 36 wk (*B*). The scales of fMCG amplitude are identical for both cases. The peak magnetic fields (B) are 5.0 pT (*A*) and 15.0 pT (*B*).

shunt through Galen malformation, reached 1330 nAm, which was the maximum value in the present study (Fig. 2).

DISCUSSION

The present study demonstrated that the approximated magnitude of the current dipole of the fetal heart at age >20 wk of gestation increases proportionately with gestational age. This trend is considered to reflect an increase in the amount of myocardial electric current or myocardial mass in parallel with fetal growth. Furthermore, this relationship is similar to the positive linear correlation between the fetal intraventricular conduction time (QRS interval) and gestational age during fetal life, reported in previous studies (4–6). Menèndez *et al.* (7) reported that the magnetic force measured on the maternal abdominal surface was larger in later than in early gestation even without correction for the depth of the heart. This is partly because the mean value of the distance between the fetal heart and the sensor coil is similar in different stages of gestation, as indicated in our study. However, the magnetic force before correction for the depth of the dipole (B) did not show a significant correlation with the gestational age in the present study. Only after correction of the B value for the depth (d_1) did the magnitude prove to correlate well with the gestational age. Therefore, the amplitude of magnetic field should be corrected for the depth of the fetal heart when we compare the value among fetuses.

Hypertrophy or enlargement of the fetal heart is diagnosed with fetal echocardiography. TCD measured on the standard four-chamber view on fetal echocardiogram is a simple index for detection of cardiomegaly (8). The mean value of TCD is known to be around the figure of the corresponding gestational age. In the present study, we selected fetuses with an enlarged heart (TCD value >95th percentile of normal) with an apparent cardiovascular structural abnormality to corroborate the usefulness of this method in detecting electric hypertrophy. Consequently, six of the seven fetuses with cardiomegaly showed larger magnitude of the dipole than the mean value + 2 SD of normal fetuses of the corresponding age. These results indicate that fMCG can be used for noninvasive and electronic evaluation of hypertrophy of the fetal heart as well as for time intervals, just like the use of MCG after birth (12) or in standard electrocardiography. Similar to TCD, it would be of interest to compare the ventricular wall thickness measured by echocardiography with the dipole magnitude, or to serially measure the dipole magnitude in the same fetus throughout

gestation for clinical evaluation. Further studies are required to evaluate the usefulness of our technique.

We approximated the magnitude of the dipole using simple equations based on the amplitude of fMCG and the distance between the pick-up coil of the SQUID system and fetal heart determined by ultrasonography. The basis for the equations is the half-space model, which is known to have certain limitations in estimating the dipole moment when applied in a clinical setting (13). Indeed, the maternal body is composed of complex conductors including vernix caseosa, amniotic fluid, and fatty layers that could affect, at least to a certain extent, the fMCG signals. Furthermore, when the fMCG signals were detected, we could observe the signals only from the currents parallel to the pickup coils' plane. Although it is important that the method can be easily applied in each case in a clinical setting, the sensor array of the gradiometer was placed parallel to the maternal abdominal surface regardless of fetal presentation (14). As a result, the magnitude of the dipole estimated from the normal (z) component of fMCG inevitably depends on the orientation of the heart or the direction of the dipole, making it smaller. In other words, if all components (x, y, z) of fMCG could be measured to calculate the magnitude of the dipole, the estimated value would be larger. Actually, as shown in Table 2, there is a marked difference in the dipole magnitude between cases 5 and 6, in which both gestational age and TCD are identical. We could not determine the exact reason for the difference, but fetal orientation, fetal motion, and complex conductors around the fetal heart might have affected the results. The heart in case 5 was in a vertical position with the apex directed downward, whereas in case 6 the heart was in a horizontal position with the apex directed rightward.

This kind of error should be corrected, if possible, for the angle of the dipole to the sensor array plane. However, such correction is difficult to realize because the fetus can move and change the orientation after sonographic examination. To partially compensate for this limitation of the methodology, we used the multichannel SQUID system and selected the tracing showing the maximum amplitude among nine channels. When the polarity or amplitude fluctuated even in the same tracing with the clearest waveform among nine channels, we adopted beats with the highest QRS amplitude on the same channel for signal averaging. Furthermore, we also estimated the magnitude of the dipole in a sufficient number of normal fetuses at various gestational ages, and the results were compared with those of enlarged hearts to validate the usefulness of the method in electronically detecting cardiac hypertrophy. It should be emphasized that, with this procedure, we could electronically differentiate cardiomegaly from a normal sized heart.

In conclusion, the present study demonstrated that fMCG recorded with a multichannel SQUID system is clinically useful for determination of the amount of the myocardial current and detection of prenatal hypertrophy or enlargement of the fetal heart electronically. However, development of postprocessing procedure to correct for the angle of the dipole to the sensor array plane and for the shift in fetal orientation during measurement is desirable for detailed evaluation of the myocardial current.

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