ABSTRACT
The aim of this paper is to describe impacts of fetal magnetocardiogram on clinical managements of fetal cardiac diseases. We used a system with 64-channel SQUID sensors. Fetal magnetocardiograms were especially useful for the diagnosis of fetal Wolff-Parkinson-White syndrome and fetal QT prolongation by measuring PR, QRS and QT intervals in magnetocardiogram. These findings were of benefit to selecting drugs of intrauterine therapy. Long-duration, 20 minutes, recording of magnetocardiogram was almost stable except for the duration with large fetal movements and was useful for denying paroxysmal attacks of life-threatening arrhythmia. However, there were a few minor problems such as maternal back pains and supine hypotension syndrome due to the nature of pregnant woman. Avoiding maternal back pains and supine hypotension syndrome, and decreasing fetal movements may be needed for the better use of long-duration magnetocardiogram.

KEY WORDS
magnetocardiogram, fetus, WPW syndrome, long QT, long-duration recording

1. INTRODUCTION
Magnetocardiography (MCG) has been recently improved and also applied to various fields of clinical medicine. Especially, fetal MCG (FMCG) is one of the most useful applications of MCG because it is rather difficult to record fetal electrocardiogram (ECG) because of vernix caseosa, which covers fetal surface skins and has very low electric conductivity even if it is apparent that ECG is one of the best diagnostic methods in cardiology. Magnet flux can pass through vernix caseosa, amnion and uterine wall, and even through pregnant maternal body, and therefore FMCG has been recognized as the best alternative diagnostic method for fetal cardiac diseases. Even if the first successful recording of FMCG was published nearly three decades ago [1], FMCG had not been widely available because of the low signal level of FMCG (nearly pico-tesla orders). Recent progress in superconducting quantum interference device (SQUID) succeeded in breaking through the difficulty.

In this paper, we showed cases of fetal cardiac diseases in which FMCG was useful in clinical managements. We also mentioned several practical problems in using FMCG.

2. METHODS
2.1 Patients
Forty-seven cases were included in this study. All the cases were referred to Department of Perinatology, National Cardiovascular Center, Osaka, Japan, due to the suspicion of fetal cardiac diseases; 20 cases were suspected of fetal arrhythmia, 17 cases were suspected of congenital structural heart diseases, and 10 cases were suspected of other cardiac diseases. Final confirmed diagnosis was made after birth by ECG, ultrasonography and other diagnostic equipments, moreover by operation findings, and by autopsy in dead cases. All the MCG measurements were begun after the patient's fully written informed consent. This study was approved by the local ethics committee.

2.2 MCG
The 64-channel SQUID system (MC-6400, Hitachi, Tokyo, Japan) installed in National Cardiovascular Center was applied for recording FMCG. The system is composed of a bed and a cryostat filled with liquid helium placed in a magnetically shielded room. The SQUID sensors were mounted in an 8 x 8 arrangement at intervals of 25 mm in the cryostat. The diameter of the pick up coil was 18 mm and the baseline length was 50 mm. The steps of the measurement procedure are shown in Fig. 1. The maternal ECG was recorded simultaneously to eliminate maternal MCG signals afterwards.

On the day of measurement the mother lay down on a bed after a 10-min walk. Before the patient's admission to the magnetic shielded room, the potion of fetal heart was verified by B-mode ultrasonography. The mother lay on her back with a small cushion bustle. The sensor array was centered just over the fetal heart. The FMCG was recorded for 2 min, on occasion 20 min. After the measurement we performed filtering (a high-pass filter and a notch filter) and removed maternal signals. Then we calculated averaged FMCG (AFMCG), and generated current-arrow maps if necessary. We did not mentioned details of principles and applications of current-arrow maps in this report because we had reported the advantages of current-arrow maps previously [2, 3].
3. RESULT

We successfully recorded FMCG in the fetuses after 26 weeks’ gestation. Here we describe three topics in which FMCG was useful for diagnosing fetal diseases.

3.1 Wolff-Parkinson-White (WPW) syndrome

In a case of mild fetal hydrops due to paroxysmal tachycardia, we successfully recorded FMCG with characteristics of WPW syndrome. The AFMCG (Fig. 1B) calculated from raw FMCG signals (Fig. 1A) showed short PR and wide QRS with characteristic delta wave. We selected propranolol for transplacental therapy and avoided administration of digoxin. We successfully made cardioversion in two days and fetal hydrops disappeared shortly.

3.2 Prolonged QT interval

We recorded prolonged QT intervals in five cases; one case of familial long QT syndrome, two cases of congenital structural heart diseases and two cases of congenital complete heart block (CAVB). We showed three typical example cases in Fig. 3. All of the QT intervals were longer than the fetal standard value, 247±34.4 msec [4]. All the fetuses with prolonged QT interval showed fetal profound (2 CAVB cases) or mild bradycardia (other 3 cases). In 2 CAVB cases and a long QT syndrome case, we did not changed clinical management only by encountering fetal bradycardia.

3.3 Long-duration recording of MCG

We recorded FMCG for consecutive 20 min in four cases of fetal arrhythmia because all of the four cases had a possible risk of life-threatening paroxysmal arrhythmia. In all of the cases, we could successfully recorded FMCG for continuous 20 min and detected no arrhythmic attack. We showed an example of FMCG recording in Fig. 4. During the measurement, FMCG levels became small when the
mother felt gross fetal movement. She also felt mild faint and had mild nausea just after the measurement, and soon relieved by lying on her side. Her symptoms might be due to supine hypotension syndrome.

\[ \begin{align*}
2 \text{ pT} \\
-2 \text{ pT}
\end{align*} \]

**Fig. 4.** Twenty minutes recording of fetal magnetocardiogram in a case with the risk of paroxysmal tachycardia. Hatched line with subscript M indicates the duration when the mother felt gross fetal movements.

4. DISCUSSION

4.1 Impacts of MCG on the management of fetal cardiac diseases

At present many fetal diseases can be diagnosed mainly by ultrasonography, but the therapy for the disease is still remained difficult. Although procedures for fetal therapies such as cordocentesis, fetoscopy and fetal surgery are invasive to the fetus and the mother, the therapy for fetal arrhythmia is less "invasive" because anti-arrhythmic drugs administrated to the mother reach the affected fetus via a transplacental route and usually effective to the fetus [5, 6]. Although digoxin is well known to be contraindicated in adult or child cases of WPW syndrome, the drug has been widely used for the fetal therapy because perinatologists had no effective tool to diagnose fetal WPW syndrome. Prenatal diagnosis of fetal WPW syndrome has been also reported by a few authors [7-9], all of whom used MCG for the diagnosis. Prevalence of MCG will refrain obstetricians from administrating such contraindicated drugs.

Long QT syndrome has been also difficult to diagnose in utero and its prenatal confirmed diagnosis was first reported in 1999 [10]. The diagnosis and subsequent reports of the successful diagnosis [11, 12] were also made by MCG. Long QT syndrome is directly related to the attack of life-threatening arrhythmia such as ventricular flutter or Torsades de Pointes. Prolongation of QT interval also caused by several drugs or many combinations of commonly used drugs. Although clinicians care for the side effects associated with QT prolongation, obstetricians have not paid attention to the side effects on fetuses because of lack of the effective diagnostic method. MCG may be also helpful to avoid the fatal risk to the fetus affected with long QT.

4.2 Long-duration MCG and related minor problems

Several arrhythmias such as extrasystoles, supraventricular tachycardia, ventricular flutter in atrioventricular block, and so on, attack the fetus paroxysmally. If the attack of such paroxysmal arrhythmias is not detected by obstetricians, the attack occasionally directly imperil the fetus. It is also recommended to monitor fetal pulses for long duration in such a case [6]. Although cardiotocography has been used for the purpose, cardiotocography monitors only pulse rates and obstetricians cannot diagnose the type of arrhythmic attack by the recording of cardiotocography. From this point of view, we tried to record FMCG for consecutive 20 min. To the best of our knowledge, long-duration recording of MCG has not been reported previously. Long-duration FMCG was successfully recorded as shown above, and however, we noticed several "minor" problems in the recording.

The mothers complained back pains which are frequent in pregnant women [13]. Supine hypotensive syndrome, which is caused by the compression on inferior vena cava by the enlarged uterus in late gestation, is also harmful to the mother [14]. Lying on the back is one of the well-known risk factors, and indeed we encountered this attack in a patient after long-duration recording of FMCG. Lying a soft cushion on the mother's hip may be a simple but effective procedure to avoid back pains and attack of supine hypotensive syndrome.

Fetal movements also worsened the quality of recording. We made the mother walk slowly for about 10 min just before she entered the magnetically shielded room, which was rather effective to decrease fetal movements during the measurement [15].

Ultrasonography has been also used for the diagnosis and managements for detecting paroxysmal arrhythmic attack of fetuses. However, ultrasonography requires continuous handling of experts for the diagnosis. MCG recording, in which the equipment requires only patient's calm lying and thus no expert's handling, may be capable of reducing expert's jobs.
5. CONCLUSION
Our clinical experiences of diagnosing fetal cardiac diseases by MCG demonstrated that FMCG can reveal WPW syndrome and QT prolongation, which has been difficult to diagnose by ultrasonography. FMCG may provide new methods of treatment with less side-effects of the therapy for fetal cardiac diseases. Long-duration FMCG was successfully recorded with a few simple means to decrease complications. MCG may give large impacts on clinical management of fetal diseases.

6. REFERENCES