FETAL MAGNETOCARDIOGRAPHY

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ABSTRACT

In fetal magnetocardiography (MCG) the magnetic field over the abdomen of a pregnant woman is measured in order to retrieve information on the electrical activity of the fetal heart. The fetal MCG shows the typical features of an ECG, e.g. P-wave and QRS-complex. The fetal MCG is a weak signal, therefore sensitive sensors are needed and disturbances, such as fluctuations of the earth's magnetic field and the fields generated by electrical devices and power-lines have to be reduced. The requirements for fetal magnetocardiography to use it as a diagnostic tool for arrhythmias and congenital heart diseases will be discussed.

INTRODUCTION

Fetal magnetocardiography (MCG) can be used for the detection and classification of arrhythmias and the study of congenital heart diseases. In fetal MCG the magnetic field over the abdomen of a pregnant woman is measured in order to retrieve information on the electrical activity of the fetal heart. Though other techniques do exist (fetal ECG, ultrasound), they either do not provide information about the electrophysiology of the fetal heart, the reliability is low, or they have a low resolution making it difficult to apply them for certain clinical applications.
The simultaneous depolarization of many heart cells cause currents in the tissues surrounding the fetal heart. As the conductivity of the amniotic fluid is higher than of the other tissues, currents are constrained within the uterus. The small part of the volume currents that reach the surface of the abdomen give rise to potential differences at the abdominal surface. A measurement of the potential difference between two electrodes attached to the maternal abdomen is called a fetal electrocardiogram. A fetal ECG thence reflects the fetal heart activity; the P-wave reflects the depolarisation of the atria, the QRS-complex the depolarisation of the ventricles and the T-wave the repolarisation of the ventricles. The fetal ECG is often too weak to be measurable. However, the volume currents as well as the currents flowing within the cardiac muscle cells give also rise to a magnetic field: the fetal MCG. The fetal MCG shows the typical features of an ECG, i.e. P-wave, QRS-complex and T-wave. That a fetal MCG can be measured is a result of the synchronic activity of many heart cells, the magnetic field of a single cell is too weak to be measurable. However, the resulting magnetic fields are still weak (less than a millionth of the magnetic field of the earth) and therefore extremely sensitive sensors are needed to measure the fetal MCG. Care is required to reduce disturbances, such as fluctuations of the earth's magnetic field and the magnetic fields generated by electrical devices and power-lines.
The aim of this paper is to discuss the requirements for fetal magnetocardiography in order to use it as a diagnostic tool for arrhythmias and congenital heart diseases. The most common fetal arrhythmia is an irregular rhythm due to isolated extrasystoles, in particular premature atrial contractions. Premature beats are beats that occur earlier than expected and briefly interrupt the normal sinus rhythm. These arrhythmias often disappear before term or within a few days after birth. However about one percent of the fetuses having premature atrial contractions, have a concomitant structural heart disease as well and about 0.5% of these fetuses are found to develop a reentrant tachycardia later on in the pregnancy. In about 50% of fetal MCGs recorded arrhythmias are found, including supraventricular and ventricular ectopic beats as well as bradycardia and tachycardia. However, the incidence of malignant arrhythmias estimated is only 0.2‰. Choosing a therapy appropriate to the arrhythmia reduces the chance of causing accelerations of the fetal heart rate or the chance of degeneration to a life-threatening arrhythmia. For this reason, it is important to know the origin of a tachycardia. Another reason for a diagnosis as precise as possible is that intra-uterine pharmacological treatment involves the administration of the cardiac medicine to the mother. This involves exposing the mother to potential side effects these agents have.

METHOD

The magnetic field sensor used is a SQUID (Superconducting Quantum Interference Device). This extremely sensitive sensor needs to be cooled by liquid helium (-269°C). Since the flux-to-voltage transfer is non-linear, the sensor is operated in a flux-locked loop. By introducing a feedback system in which the measured flux is applied to a feedback

coil next to the SQUID, the system can be used as zero-detector. In this case the flux through the SQUID is kept constant.
In order to couple the magnetic flux present near the maternal abdomen into the SQUID, a flux transformer is used. The flux transformer consists of two superconducting coils at a certain distance that are wound in opposite direction. In case this flux transformer is subjected to a homogeneous magnetic field, the net flux coupled into the flux transformer is zero. Hence, the flux transformer is sensitive for sources close to the pickup coil and not sensitive for sources far away, as these will render magnetic fields, which approach a homogeneous field at these distances. Our vector gradiometer consists of three flux transformers. The various coils are wound around the same cylinder in such way that they pick up the magnetic flux in three perpendicular directions.
The measurements take place in a magnetically shielded room, in order to avoid environmental noise. This magnetically shielded room consists of a layer of aluminium and two layers of mu-metal. In order to be as close as possible to the fetal heart, the mother is asked to lie in a supine position underneath the vessel filled with liquid helium (the so-called cryostat) that contains the SQUIDs and flux transformers. The magnetometer system can be repositioned over the maternal abdomen in order to find a good position for obtaining a fetal MCG. The recorded signals are fed to a computer system located outside the shielded room, where the signals are processed. Customarily fetal MCGs are averaged, because in the raw data often the P-wave and the T-wave are not discernible and the duration of the various waves cannot be extracted from the raw data. A signal can be averaged if the R-peak signal is clearly observable in the raw data and if enough heart cycles are measured that are correlated. Due to averaging of N PQRST complexes, the signal-to-instrumentation noise ratio increases $\sqrt{N}$ times (in terms of magnitude). The maternal MCG usually interferes with fetal MCG and is subtracted from the latter after data acquisition.
In order to optimize the fetal magnetocardiograph all noise sources have to be considered and the dominating ones have to be minimized. Measurements have shown that cryostat thermal noise can be the main sensitivity-limiting factor in a fetal magnetocardiography. If the cryostat thermal noise limits the sensitivity of the fetal magnetocardiograph, no significant improvement of the sensitivity can be achieved reducing flux noise of the SQUID and voltage noise of the readout electronics.
The noise level was estimated in one of our MCG measurements in the region below 100Hz. After subtraction of the maternal signal, the fetal MCG signal was filtered by a 1Hz high-pass filter and the QRS complexes of the fetal signals were detected. After that, the signal was divided in segments of 512 samples in length such, that the R-point of the fetal QRS complex are exactly in the middle of each segment. Then, the fetal MCG signal was suppressed subtracting adjacent segments in pairs, according to:

$$X_i = (S_{2i} - S_{2i+1})/\sqrt{2}; \qquad 0 \le i \le N/2 \tag{1}$$

X_i is a segment of residual noise signal, S_i are segments of the fetal MCG signal and N is the number of segments.
In the equation it is assumed that the variability of the fetal MCG signal from segment to segment is not significant and the subtraction cancels the fetal signal sufficiently well. Further, it is assumed that the noise segments are uncorrelated and as the result of subtraction the noise power doubles. The factor of $1/\sqrt{2}$ takes the last assumption into account. Subsequently, the power spectrum of each segment (X_i) is estimated.

REQUIREMENTS

The most common arrhythmia in a fetus are isolated extrasystoles. In order to detect them it is enough to measure the fetal heart rate with a beat-to-beat accuracy. The same is true for the diagnosis of tachycardia and bradycardia. To distinguish between a second- or third-degree atrioventricular block, it is necessary to see the P-waves and the QRS-complexes in the raw data. The same is true for atrial flutter and extrasystoles (in order to be able to determine whether the extrasystoles have a ventricular or supraventricular origin). In our experience, the P-wave is somewhat larger in case of a heart block than in normals. This may be due to hypertrophy of the atria. With fetal MCG it is possible to determine the PR-interval with an accuracy of 5ms and the RR-interval with 2ms. The fetal MCG should be recorded at several positions above the maternal abdomen because if the fetal MCG is recorded in only one position, the duration of the P-wave may be underestimated. The diagnosis of a prolonged QT-syndrome requires that the T-wave is discernable in the averaged data. To study congenital heart diseases, the duration of the P-wave, PR-interval, QRS-complex, QT-interval and T-wave should be available.
The requirements for the fetal magnetocardiograph discussed above are summarized in Table 1. The results imply that to cover most of the cases, the fetal magnetocardiograph must be sensitive enough to observe P-waves in the raw data and that T-waves are discernible in the averaged fetal MCG.

Table 1. Requirements for fetal magnetocardiography

Problem	**Nowadays diagnosed**	**Requirement for fetal MCG**
Fetal heart rate	From the 10-12th week onward by means of Doppler ultrasound	R-peaks in raw signal
Atrial flutter	Third trimester by means of ultrasound	P-waves in raw signal (flutter-waves)
Fetal extrasystoles (premature atrial/ventricular contractions)	Third trimester by means of ultrasound	P-waves and R-peaks in raw signal
Atrioventricular Block	Third trimester by means of ultrasound	P-waves and R-peaks in raw signal
Long QT syndrome	Postnatal by means of ECG	T-wave and R-peak in averaged signal
Congenital heart disease	Second trimester by means of ultrasound	PQRST complex in averaged signal

RESULTS

Fetal MCGs can be measured reliably from the 20th week of gestation onward [1]. The noise level of our fetal magnetocardiograph is better than 2fT/√Hz. Comparison of the spectra obtained with a pregnant woman underneath the cryostat and without the woman shows that the noise is dominated by contributions from the patient. For that reason the sensitivity of the fetal magnetocardiograph may be limited by noise arising from the maternal abdomen. Hence, no significant improvement of the magnetocardiograph can be expected from lowering noise of the SQUID or the readout electronics. Using this magnetocardiograph, fetal MCGs were recorded in eight patients. It was possible to distinguish the P-wave in the raw data in three records. It was also possible to distinguish the T-wave in the averaged signals.

CONCLUSION

We may conclude that our fetal magnetocardiograph enables us to classify fetal cardiac arrhythmias and to study congenital heart diseases in the fetus [2].

REFERENCE

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