Measuring Technology for Cardiac Magneto-field Using Ultra-sensitive Magnetic Sensor

—For High Speed and Noninvasive Cardiac Examination—

Keiji Tsukada, D. Eng.
Hitoshi Sasabuchi
Toshio Mitsui, MD, Ph. D.

Overview: The electrophysical process of a human heart is noninvasively visualized and analyzed by using a multichannel quantum interference device (SQUID) system. By analyzing tangential components of the cardiac magnetic field, we can observe simultaneous activated multiple regions and intracardiac current distribution in the heart. An iso-integral mapping technique is developed as new concept projecting total current image on the torso from the heart. When we compared the iso-integral map of a normal and an ischemic heart, the ischemic heart showed different patterns for the depolarization and repolarization processes. MCG measurements of fetal hearts have become easy because of improvements in the sensitivity of sensor units and the fact that magnetic measurements are not affected by fetal fat or the mother's heart. Based on these visualization and measuring techniques, we developed a 64-channel SQUID system that can be used as an MCG for analyzing vector components of a cardiac magnetic field.

INTRODUCTION

SUPERCONDUCTING quantum interference devices (SQUID) are used as ultra-sensitive magnetic field sensors to detect cardiac magnetic fields generated by the heart. Multichannel SQUID systems for magneto-cardiograms (MCG) have been developed by improving SQUID and cryogenic technology. Visual diagnosis for heart disease has been made possible by using multi-points MCG data. These systems usually detect normal components (Bz) to the body surface. From the Bz magnetic field pattern in an MCG, a simple current source in the heart can be estimated (see Fig. 1). This simplified model is adequate only for detecting an initial localized source, e.g., Wolff-Parkinson-White (WPW) syndrome. Most patterns, however, are not so simple, and they have widespread, separated active regions, which make it difficult to make a visual inspection from the Bz map. To analyze

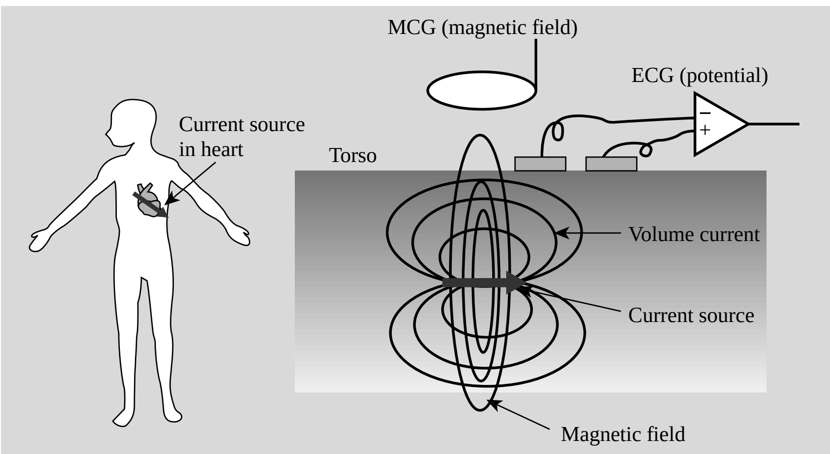

Fig. 1— A Schematic Representation of Relationship between MCG and ECG. The magnetocardiogram (MCG) and electrocardiogram (ECG) are originated from the electrophysiological phenomenon in the heart.

dynamic changes and conditions in a distributed cardiac electric process, we have developed some new display methods using tangential components (Bx and By). Using the new visualization technique, we developed a 64-channel SQUID system for analyzing vector components of a cardiac magnetic field.

MAGNETIC CARDIOGRAM

Visualization of Active Regions

We have developed a visualization technique for noninvasively analyzing the electrophysiological characteristics of the heart. The technique is based on two-dimensional projection obtained by measuring the tangential components of the MCG. The tangential components of a magnetic field ($\sqrt{Bx^2+By^2}$) show a peak pattern just above the current source, which means that the tangential magnetic field pattern is likely to be a two-dimensional current projection pattern on the observation plane.[1] Isofield maps of the front and back observation planes during the last phase of the Q wave at 22 ms, and an MRI image of the coronal cross section of the heart are shown Fig. 2 for a typical normal subject. Here, the little arrows in the figure show the direction and relative magnitude of the current. The electrocardiogram (ECG) signal is difficult to detect in the back plane because of the high resistivity of the lungs. The MCG signal at the back, however, can be easily obtained, as shown in the Fig. 2. The gradiometer output depends on the distance, so the signal strength ratio of the anterior heart and that of the posterior heart were different at the front and back. This means that the signal produced by the anterior heart is stronger than that of the posterior heart in the front plane, and vice versa in the back plane. We can see two peaks in the front map and one peak in the back map. The location of the maximum point of the posterior active region was slightly higher than that of the anterior active region, and the direction of the current was different between the front and back. This tangential isofield mapping method makes it easy to visualize the electrophysiological behavior of the heart.

Iso-integral Mapping

The iso-magnetic field maps show a dynamic electrophysiological change in the heart. However, while these maps are useful for identifying temporal changes such as these caused by arrhythmia or conduction blocks, diagnosing ischemia is sometimes difficult by only observing dynamic changes. In a

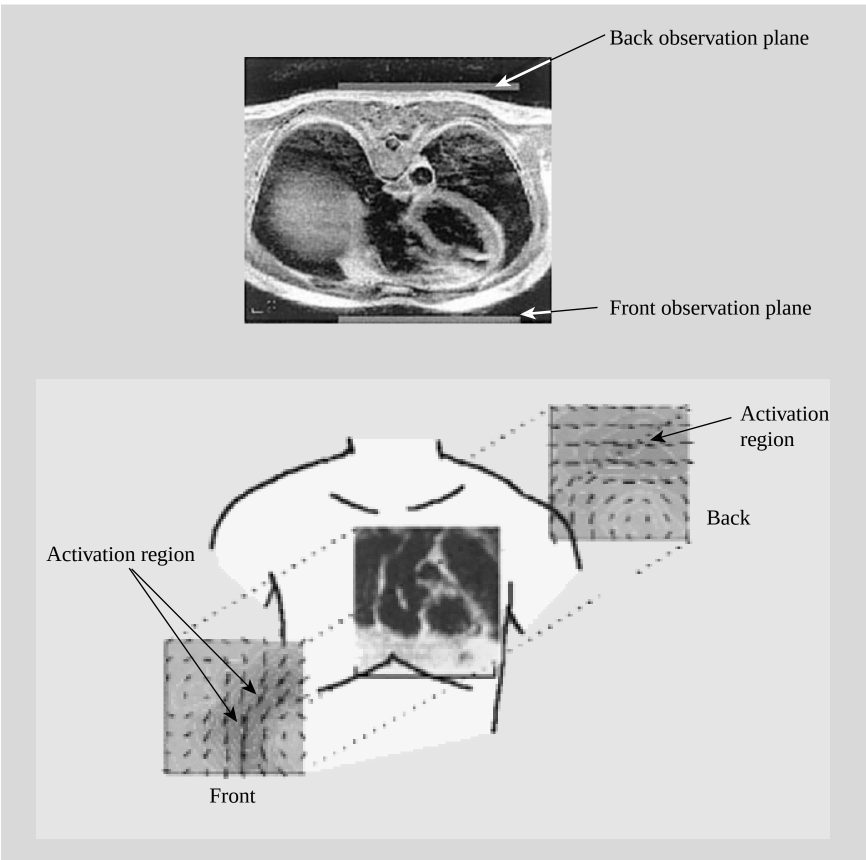

Fig. 2— Anterior and Posterior Isofield Maps, and the Relationship between Observation Planes and the Position of Heart.
The isomagnetic field maps are obtained by connecting the same magnitude point of tangential magnetic field. The little arrows show the direction and relative magnitude of the current.

tangential magnetic field map, the area between the strong magnetic field and the current source is coincident. This coincidence enables us to obtain a projected total current image by using an iso-integral of Bxy. Therefore, we examined the possibility of using iso-integral maps for diagnosing ischemic heart disease.[2] The cardiac activation process in the ventricle is divided into depolarization (QRS) and repolarization (ST-T). Examples of the iso-integral maps from a normal subject and an ischemic heart are shown in Fig. 3. The iso-integral map of the normal subject shows a similar pattern for both the depolarization and the repolarization. The maximum value region is located in the position of the left ventricle. On the other hand, the iso-integral map of the acute ischemic heart showed differences between QRS and ST-T. These differences might be due to current perturbations caused by ischemic parts. That is, the current flow in the ischemic part becomes randomized and total current becomes weaker. Comparing iso-integral maps of depolarization and repolarization is thought to be a promising method for diagnosing ischemic heart disease.

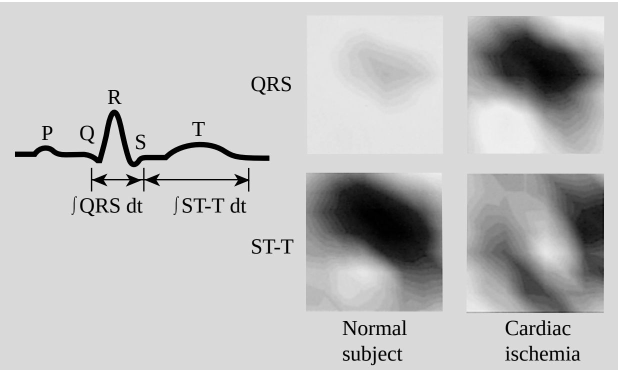

Fig. 3— Iso-integral Maps of a Normal Subject and Ischemic Heart.
Compared with iso-integral maps for depolarization process (QRS) and repolarization process (ST-T), there was a clear difference between both processes in the case of an ischemic heart.

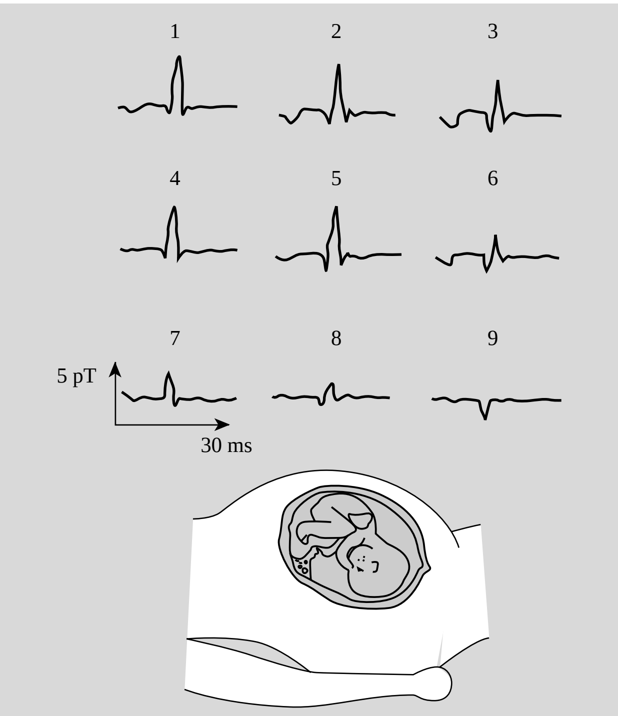

Fig. 4— Typical Fetal MCG Signals (averaged 50 times).
Typical maximum magnitude of fetal MCG is about 5 pT *which is about 10% in comparison to adult's MCG, The fetal MCG measurement is a noninvasive diagnosis method.*

Fetal Magnetocardiogram

For fetal heart diagnosis, ultrasounds or fetal electrocardiograms (FECGs) have been used. Ultrasound diagnostic systems can provide some information about the heart activity, structure, and blood flow. FECG using an electrode placed on the mother's abdomen provides electrophysiological information such as arrhythmia or detects for variations in the heart beat. Fetal magnetocardiograms (FMCGs), in contrast, can be taken over the abdominal surface without the interference of amniotic fluid, and vernix caseosa. Furthermore, there is little interference from the maternal MCG because the strength of a magnetic field is inversely proportional to the square of the distance to the source of that field.[3]

Fig. 4 shows typical FMCG signals obtained by averaging 50 readings. Maximum magnitude of the magnetic field is about 5 pT, which is about 10% of an adult's MCG. The FMCG measurement is thus an easy, noninvasive method of diagnosing fetal heart disease. Compared with the signals of a fetal electrocardiogram, signals of FMCG are easily obtained with a higher resolution.

MCG SYSTEM

We developed a 64-channel SQUID system that analyzes the vector components of a cardiac magnetic field. The system is compact and requires fewer SQUID sensors for visually recognizing active areas in the heart.[4] MCG tangential components have an advantage in the visual recognition of active areas in the heart. However, a system that measures tangential components needs more SQUIDs and measuring circuits than a SQUID system that measures Bz

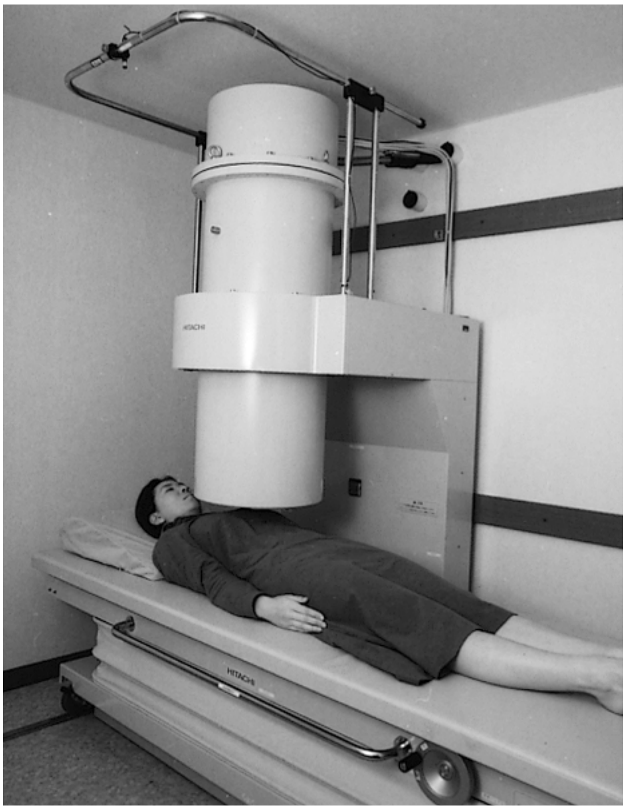

Fig. 5— Photograph of 64-channel SQUID System for MCG.
The MCG system provides electrophysiological information in the heart without any physical contact with the patient.

components. To reduce the number of SQUIDs and measuring circuits, we developed an analysis technique for deriving two tangential components (Bx, and By) from the measured Bz component without directly measuring the tangential components. An MCG system is shown in Fig. 5. A Dewar vessel is held on a stand fixed to the floor, and the bed can move in the x, y, and z directions to adjust the gap and position between the Dewar and the torso. Measurement is done inside a magnetically shielded room (MSR) having a double µ-metal layer. A SQUID probe is placed at each of the 64 sites in an 8 ¥ 8 matrix with 25-mm intervals, giving a measurement area of 175 ¥ 175 mm. The typical noise of the system is less than 20 $fT/\sqrt{Hz}$. Two types of magnetic-field pattern are obtained at the same time. The position and distribution of a current source in the heart can be analyzed and visualized.

CONCLUSIONS

We introduced new aspects such as multiple cardiac active regions, iso-integral map in ischemic heart, fetal MCG, and display method using tangential magnetic field that is useful for making easy to visualize the electrophysiological behavior of the heart. MCG is a noninvasive examination procedure that takes just a few minutes without any physical contact with the patient. However, since it is very important to save both time and money in the medical field, this examination technique should be compared with other diagnostic examination techniques. Further evaluation of MCG will reveal more new information. We believe MCG is a promising tool for diagnosing heart disease.

REFERENCES

(1) K. Tsukada, et al., "Multichannel SQUID System Detecting Tangential Components of the Cardiac Magnetic Field," *Rev. Sci. Instrum.* **66**, 5085 (1995).
(2) M. Sato, et al., "Diagnosis of Ischemic Heart Disease by an Isointegral Mapping Using Tangential Magnetocardiogram," 11th International Conference on Biomagnetism, Sendai (August 1998).
(3) H. Hamada, et al., "Prenatal Diagnosis of Long QT Syndrome Using Fetal Magnetocardiography," (to be published in Prenatal Diagnosis, 1999).
(4) K. Tsukada, et al., "A Simplified Superconducting Quantum Interference Device System to Analyze Vector Components of a Cardiac Magnetic Field," International Conference on IEEE EMBS, Hong Kong (1998).

ABOUT THE AUTHORS

Keiji Tsukada
Joined Hitachi, Ltd. in 1982, and now works at the Medical Systems Div., Central Research Laboratory. He is currently engaged in the development of bio-magnetic instruments and magnetic resonance imaging. Dr. Tsukada is a member of IEEE, and can be reached by e-mail at ktsukada@crl.hitachi.co.jp

Hitoshi Sasabuchi
Joined Hitachi, Ltd. in 1971, and now works at the Instruments group. He is currently engaged in the development of bio-magnetic instruments. Mr. Sasabuchi is a member the Japan Biomagnetism and Biomagnetics Society, and can be reached by e-mail at sasabuti@cm.naka.hitachi.co.jp

Toshio Mitsui
Toshio Mitsui received his Ph. D. from Tokyo University in 1966. Currently he is a professor at the Institute of Clinical Medicine, University of Tsukuba. Dr. Mitsui is a member of Japan Surgical Society.