Newly Developed Magnetocardiographic System for Diagnosing Heart Disease

Keiji Tsukada, D.Eng.
Kôichi Yokosawa, D.Eng.
Akihiko Kandori, D.Eng.
Hitoshi Sasabuchi

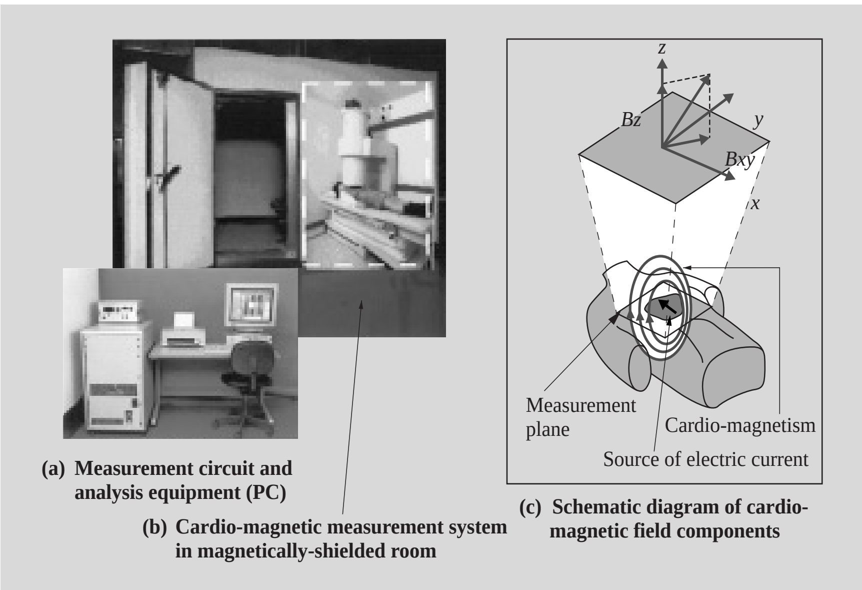
OVERVIEW: An innovative system based on SQUIDs (superconducting quantum interference devices) for multi-point measurement of ultra-weak magnetic fields emitted from the heart (magnetocardiograph) has been developed, which permits the measurement of cardio magnetic fields across a wide age spectrum from fetus to mature adult. A range of different techniques for mapping the cardio magnetic fields permits noninvasive visualization of electrophysiological activity in the heart and direct read-outs with little or no experience. In conjunction with clinical research, these new analytical methods also lay the groundwork for an array of analytical tools that can be used to support the diagnosis of arrhythmia, ischemic heart disease, and other heart disease. It is widely anticipated that these technologies developed by Hitachi, Ltd. will open the way to a range of powerful diagnostic techniques that can be applied easily, quickly and accurately to anyone for the early detection and assessment of a wide range of abnormal heart conditions and diseases.

INTRODUCTION

HEART disease ranks alongside cancer and stroke (cerebrovascular disease) as primary cause of death, and the early diagnosis and treatment of coronary conditions is a high-priority concern of the worldwide medical community.

Intra- and extra-cellular ionic activity associated with muscular activity of the heart is manifested as electrical current. The current generates not only as change in electric potential on the surface of the body that can be picked up by an electrocardiography (ECG), but also as variation and change in magnetic fields. The weak magnetic signals associated with electrical activity in the heart are less than 10^{-10} tesla, some six orders of magnitude weaker than the earth's magnetic field of 10^{-4} tesla. For this reason, measurement systems based on SQUIDs are typically implemented as multi-channel arrays.

The characteristics and reliability of SQUID devices have been considerably improved over the last



B_{xy}: tangential components of magnetic field
B_z: normal components of magnetic field

Fig. 1— Abnormalities of the Heart Can Now Be Detected by Using a Magnetocardiograph to Noninvasively Measure Changes in Electrophysiological Activity of the Heart and Representing the Waveforms Visually.

few years, to the point that they are now being implemented as multi-channel arrays. This enables full coverage of the heart with a single measurement scan, analysis of each and every heartbeat, and precise mapping with a high degree of spatial accuracy. Hitachi, Ltd. is in the forefront of this field as demonstrated by its recent development of a state-of-the-art 64-channel magnetocardiograph. The increasing sensitivity of SQUIDs has expanded their potential range of applications to include the detection of ultra-weak signals emitted from fetal cardio-magnetic fields and the development of new analytical tools for diagnosing abnormal heart conditions such as arrhythmia and ischemic heart disease.

Based on leading-edge developments in a number of SQUID-related technologies, Hitachi, Ltd. has developed an innovative new system for measuring cardio-magnetic fields. This paper provides an overview of the system that employs magnetocardiograms (MCGs) as a powerful new tool for diagnosing a range of heart diseases.

SQUIDS

Fig. 2 shows a schematic representation of a SQUID (superconducting quantum interference device).[1] SQUID chips can be mass-produced in much the same way as integrated circuits by depositing thin films onto silicon wafers using photo-fabrication technology.

The superconducting layer in a typical SQUID device consists of niobium (Nb). Josephson junctions consist of a thin layer of insulating aluminum oxide (AlO_x) sandwiched between layers of superconducting niobium, a device exhibiting a tunneling effect. In designing a SQUID device, the fundamental parameters are size of the washer ring hole, number of windings of the input coil, the shunt resistance, and the critical current of the Josephson junction. A SQUID device that is ideally suited for magnetocardiography can be fabricated by optimizing these various parameters. The detection sensitivity of the SQUID used in Hitachi's magnetocardiograph is such that it can measure cardio-magnetic fields across a frequency range of 1–100 Hz and having a very high SN ratio of less than 10 $fT/\sqrt{Hz}$ (where f is 10^{-15}). Applications for SQUID devices are by no means confined to magnetocardiography, for there are many potential applications for these highly sensitive magnetic sensors.

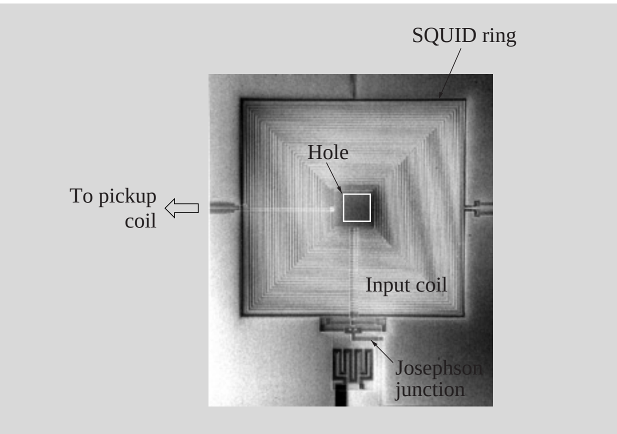


Fig. 2— SQUID Configuration.
Very weak magnetic fields emitted by the heart are easily detected with a SQUID using superconducting magnetic sensors.

MAGNETOCARDIOGRAPH

Hitachi, Ltd. has now developed MC-6400, a 64-channel magnetocardiograph designed specifically to measure cardio-magnetic fields.[2] Photograph (b) in Fig. 1 shows what the MC-6400 system looks like. The system bed can be moved in three directions — x, y, and z — to ensure that the magnetic sensors and chest region or heart are in ideal alignment. The measurements are performed in a conventional magnetically-shielded room, and the patient remains fully clothed during the examination. The magnetic sensors are capable of measuring the DC component as a frequency response characteristic, and employ a gradiometer that is connected to a 1st order differential coil made of superconducting wire and the SQUID. The combination of the differential coil and magnetically-shielded room creates a biomagnetic measurement environment with low ambient magnetic noise. The gradiometers and other superconducting components are maintained at superconducting temperatures by immersion in a bath of liquid helium in a cryogenic dewar. As shown in Fig. 3, the array of

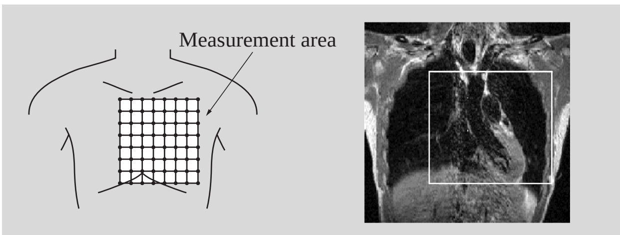


Fig. 3— Measurement Area of Magnetocardiograph.
The system is capable of measuring a heart (ranging in age from fetus to mature adult) in a single scan and with a resolution of a single heartbeat.

magnetic sensors was arranged on a flat 8-by-8 grid with 25-mm spacing between the sensors to create a large 175 mm by 175 mm measurement area capable of obtaining an MCG reading for an adult heart in a single scan. The time waveform for each channel can be measured at a minimum time resolution of 0.5 ms, and the data from each of the 64 channels can be stored on a PC for later analysis. Note that ECGs and other kinds of signals can be captured by the system as well.

MAGNETOCADIOGRAM

Time Waveforms and Their Mapping

The 64-channel cardio-magnetic time waveforms can be displayed either as separate waveforms for each point or as superimposed waveforms, and signal strength, time and time width can be read out for any phenomenon. The magnetic field distribution, or iso-magnetic field maps, can also be displayed for any interval of time. The magnetic fields are divided up into x, y, and z vector components. Note that the system does not measure these three components. Rather, a normal component iso-magnetic field map is produced from the normal magnetic field components Bz and tangential components and equivalent iso-magnetic field components combining the x and y components that are perpendicular to the normal magnetic field components are displayed for the chest area that is directly measured by the system's magnetic sensors. Fig. 4 shows the time waveform of the cardio-magnetism, and the iso-magnetic field map of the tangential components derived from the normal components of each phenomenon. Arrows are superimposed on the iso-magnetic field map to convey an intuitive understanding of the direction and magnitude of current in the heart. The strengths of the magnetic fields in the iso-magnetic field map are represented as contour lines, and the darker the color the stronger the field.

From the conventional display of normal components used in MCGs, one could only guess at the source of the current, and therefore could not obtain a direct reading of activity inside the heart. The advantage of displaying tangential components is that there is a one-to-one relationship between the strength of current in the heart and the strength of magnetic fields on the measurement area. This means that anyone—even someone with little or no experience—can easily obtain a read-out of the region of the heart where the activity is occurring and the direction that the current is flowing. The iso-magnetic field map shows the ventricular depolarization process (*QRS* complex), and reveals that excitation begins with the ventricular septum, then moves from the right ventricle to the left ventricle. The MCG thus provides a graphic picture of the direction current flows in the heart muscle and the region in which the activity is occurring.

Estimating Arrhythmia

Arrhythmia is a primary contributing factor in many diseases. Identifying regions of abnormal pre-excitation of premature ventricular contractions, or WPW syndrome is extremely important for making an accurate diagnosis, and techniques to visualize circulatory processes and furnish 3D images of affected regions have long been sought.

Fig. 5 shows an example of premature ventricular contraction, in which a 3D projection of the early excitation region is derived, then superimposed on an MRI (magnetic resonance imaging) slice. From the

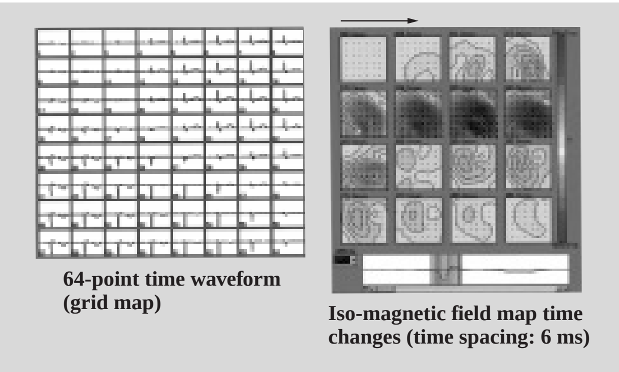


Fig. 4— Magnetocardiogram.
64-point cardio-magnetic time waveform and magnetic field distribution changes measured by Hitachi's model MC-6400 magnetocardiograph.

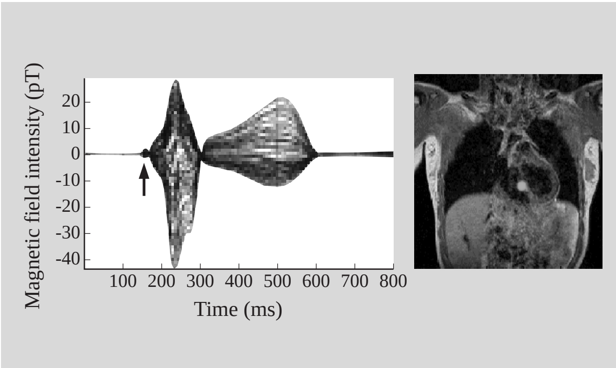


Fig. 5— Arrhythmia Examination Example.
The anatomical location can be read directly by estimating the region of early arrhythmia (premature ventricular contraction) excitation and superimposing the data on an MRI image.

results, one can estimate that arrhythmia originated in the vicinity of the free wall of the right ventricle of the heart. By thus solving the reverse problem of estimating the sources of electrical current from the magnetic field distribution, one can identify the location and magnitude of the current source localizing the arrhythmia. This new capability should enable doctors to examine the area to be treated beforehand (such as for catheter ablation) and judge the likely recovery.

Ischemic Heart Disease

Ischemic heart disease is classified as a lifestyle-related heart condition, and its rate of morbidity increases with age. An ischemic condition resulting from temporary insufficient flow of blood reaching the heart muscle can easily progress to an infarction due to necrosis of the heart muscle (death of a portion of tissue due to loss of blood supply), thus escalating to a serious condition. At the beginning of an ischemic state, the condition is reversible; that is, the ischemia appears when a heavy load is put on the heart—say, during exercise—then recedes when the person is at rest. Unfortunately, this greatly reduces the probability of detecting ischemia early, and makes diagnosis difficult.

A new method of examining for ischemia using magnetocardiography was recently proposed[3]. A magnetocardiogram captures the current distribution at a particular instant, but total current flow in the heart muscle can be derived with an iso-integral map that integrates a number of MCG time shots. Particular attention is focused on changes in the total current distribution for the ventricular depolarization process (*QRS*) and repolarization process (*ST-T*). Iso-integral maps for each process are compared in Fig. 6. One can see from the results that, for a normal healthy individual, there isn't much difference between the current volume distributions of the *QRS* and *ST-T*. One of the significant new findings of recent work with these iso-integral maps is that, when an ischemic condition is involved, there is a fairly substantial difference in the *QRS* and *ST-T* distribution patterns. This means that the distinctive tell-tale repolarization abnormality caused by ischemia can be identified with a single scan of the distribution.

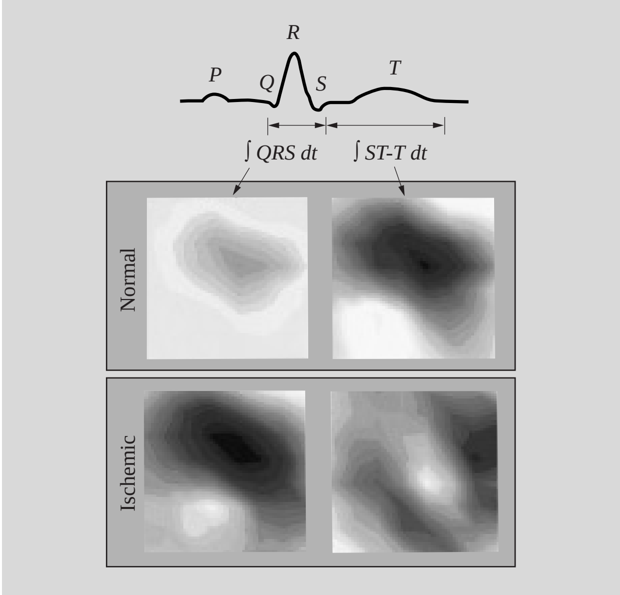


Fig. 6— Ischemic Heart Disease Example.
The total current distribution flowing through the heart muscle can be visualized as an image by using an iso-integral map. The figure reveals the occurrence of an abnormal repolarization process (ST-T) current distribution due to ischemia.

Fetal MCG

Measuring the electrical attributes of the fetal heart while knowing the developmental state of the heart is very useful for assessing the health and development of the fetus. Cardio-magnetism of the fetus can be readily detected by magnetocardiography without being the least affected by the electrically insulating vernix caseosa layer (covering dead cells that protect the skin of the fetus) that forms around the fetus after the first 24 weeks in the womb. Considering that MCG has no adverse effects on the fetus or on the mother, research on the cardio-magnetism of fetuses has been substantially expanded in recent years as magnetic sensors have become more sensitive.

Fig. 7 shows the cardio-magnetic waveform of a healthy fetus measured by a 64-channel magnetocardiograph. Not only is the *QRS* wave clearly depicted, but the *T* wave can also be discerned. An

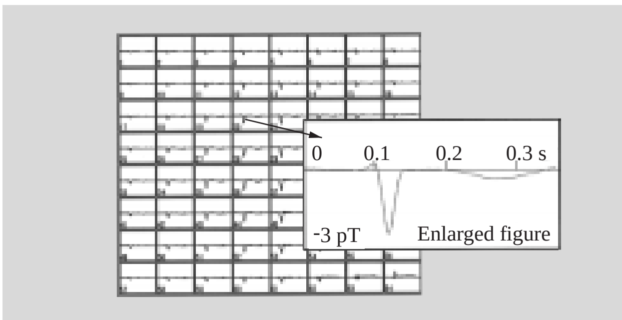


Fig. 7— Fetal Magnetocardiogram Example.
Magnetocardiography can readily pick up electrophysiological phenomena that are hard to detect by using conventional electrocardiography.

enlarged waveform for a single channel is shown in the same figure for clarity. To maximize the detection efficiency of the fetal cardio-magnetism, a special apparatus is being developed that is titled to the shape of the mother's abdomen. This brings the fetus and the magnetic sensors into the closest proximity, which aids in measuring the strongest magnetic field components[4].

Fetal magnetocardiography has already brought the first success in detecting long *QT* syndrome, a condition that has been implicated as a primary factor in causing sudden infant death syndrome[5]. We are optimistic that this research will open the way to powerful new fetal diagnostic methods.

CONCLUSIONS

This paper provided an overview of Hitachi's state-of-the-art system for measuring cardio-magnetic fields using magnetocardiograms (MCGs) for the diagnosis of heart diseases.

Besides Japan, researchers in Germany and Finland have also taken an active interest in developing new applications for magnetocardiography. Recent reports have by no means just been confined to the engineering aspects of magnetocardiography, but numerous clinical studies relating to MCG have also been reported. A great deal of new knowledge about the potential of magnetocardiography is thus likely to become available in the near-term future. Note that much of this new knowledge could not be learned by any other approach or technology. As a noninvasive technique, moreover, magnetocardiography will eventually see extensive applications in support of routine examinations and preoperative treatment plans, monitoring postoperative decisions, and diagnosing fetuses before birth. Encouraged by the applicability of magnetocardiography to virtually any and everyone and the ability to detect illnesses and arrive at appropriate treatment plans at an early stage, we intend to pursue MCG-related research in the coming years.

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ABOUT THE AUTHORS

Keiji Tsukada

Joined Hitachi, Ltd. in 1982 and now works at the Medical Systems Department of the Central Research Laboratory. He is currently engaged in the development of biomagnetic measurement systems. Dr. Tsukada holds a doctorate in engineering, and is a member of the IEEE, the Japan Society of Applied Physics, and the Japan Society of Medical Electronics and Biological Engineering, and can be reached by e-mail at ktsukada@crl.hitachi.co.jp.

Kôichi Yokosawa

Joined Hitachi, Ltd. in 1986 and now works at the Medical Systems Research Department of the Central Research Laboratory. He is currently engaged in the research and development of cardio-magnetic measurement systems and superconducting quantum interference devices (SQUIDs). Dr. Yokosawa holds a doctorate in engineering, is a member of the Japan Society of Applied Physics, and can be reached by e-mail at yokosawa@crl.hitachi.co.jp.

Akihiko Kandori

Joined Hitachi, Ltd. in 1990 and now works at the Medical Systems Department of the Central Research Laboratory. He is currently engaged in the development of biomagnetic measurement systems. Dr. Kandori holds a doctorate in engineering, and is a member of the Japan Society of Medical Electronics and Biological Engineering and the Institute of Electronics, Information and Communication Engineers, and can be reached by e-mail at kandori@crl.hitachi.co.jp.

Hitoshi Sasabuchi

Joined Hitachi, Ltd. in 1971 and now works at the Medical Systems Cluster of the Instruments of the Central Research Laboratory. He is currently engaged in the development of biomagnetic measurement systems. Mr. Sasabuchi is a member of the Japan Biomagnetism and Biomagnetics Society, and can be reached by e-mail at sasabuti@cm.naka.hitachi.co.jp.