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SQUID Systems for Magnetocardiographic Applications

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Abstract-- **As very sensitive magnetic field sensors, superconducting quantum interference devices (SQUIDs) are used to measure magnetic field signals from the human heart. By analyzing these cardiomagnetic signals, functional diagnoses of heart can be done. In order to measure weak biomagnetic signals, we need a multichannel SQUID array with sensor coverage large enough to cover the whole heart to enable the measurement in a single position setting. In this paper, we review the recent development of SQUID systems for measuring cardiomagnetic fields, with special emphasis on SQUID types.**

1. INTRODUCTION

Electric currents in the myocardium generate magnetic fields, called magnetocardiogram (MCG), which can be measured outside of human chest using magnetic sensors. By measuring and analyzing these magnetic signals, functional information on the heart can be done. Recently, MCG was shown to have accurate diagnostic performance in predicting the acute coronary disease, and MCG seems to be a promising medical device for the diagnosis of ischemia, especially in emergency room [1-4]. These cardiomagnetic signals, however, are very weak, typically in the range of 1 pT – 100 pT in amplitude, with a frequency range of 0.01 Hz – 100 Hz. Thus we need very sensitive magnetic sensors and have to reduce the environmental noises sufficiently.

Recently developed low-noise superconducting quantum interference devices (SQUIDs) have field sensitivities of few fT/√Hz in the white region, and SQUIDs can be used to measure most of these signals. In measuring weak signals, sensitivity is of primary importance to provide good signal-to-noise ratio. In practical multichannel systems where number of sensors is around 60 in MCG, mass fabrication or productivity, reproducibility or uniformity of fabrication, reliability again long-term thermal cycling are also important [5-7].

In order to suppress the environment magnetic noises, typically magnetically shielded room is used. Since the high permeability sheet is expensive and thick shielded room is heavy, gradiometry is used which selectively measure signals from the nearby sources and reject strong yet uniform environment fields.

In constructing a biomagnetic system, suitable combination of SQUID pickup coil and shielded room is needed. Magnetometer provides best sensitivity to deep sources, but need a thick or heavy shielded room to have good signal-to-noise ratio (SNR). Depending on the baseline length, gradiometers provide diverse sensitivity to depth of the sources. Typically axial gradiometers have a baseline of about 5 cm. First-order gradiometer having a baseline of 5 cm and operating in a moderately shielded room provides suitable SNRs for shallow or mid-depth sources, but low SNRs for deep sources. Second-order gradiometers have lower productivity in fabrication, but they can be operated in thin shielded room or in unshielded condition.

Most of the SQUIDs used in the biomagnetic systems were made of Nb Josephson junctions and Nb wires. To maintain the SQUID in the superconducting state, cooling by liquid He is needed. Nearly all cooling devices, dewar, are made of fiberglass reinforced plastic (FRP), usually called G-10 or G-11. When optimizing the dewar shape to accommodate the large number of sensors, thermal noise from the vacuum part of the dewar where SQUIDs are distributed should be minimized while keeping the boil-off rate of the liquid He small.

2. MCG SYSTEMS

2.1. Types of SQUID Pickup Coils

Electric activity of myocardium cells generate magnetic fields which can be measured by using multichannel SQUID sensors. Several commercial MCG systems were developed with sensing SQUID numbers of 4 (MAGIC, Germany), 9 and 36 (CMI, USA), 55 (AtB, Italy), 64 (Hitachi, Japan), 67 (4D Neuroimaging, USA) [2]. In KRISS, we have developed several MCG systems with channel numbers of 61 or 64, each having different types of pickup coils, magnetometer, planar gradiometers and axial gradiometers. Features of worldwide MCG systems developed recently were summarized in Table I. Several examples of pickup coils are shown in Fig. 1.

TABLE I
COMPARISON OF SEVERAL MCG SYSTEMS.

	Hitachi	ATB	Neuromag	4-D Neuro-imaging	CMI	MAGIC	KRISS
Country	Japan	Italy	Finland	USA	USA	Germany	Korea
Channel	64	55	99	67	9 (36)	4	61, 64
Pickup coil	Axial, 1^{st}-*order*	Magne-*tometer*	Planar, 1^{st}-*order*	Magne-tometer	Axial, 2^{nd}-order	Axial, 2^{nd}-order	Planar, $1^{st}(2^{nd})$-order Axial, $1^{st}(2^{nd})$-order
Shielding	*Moderate*	*Heavy*	*Moderate*	*Heavy*	*No shield*	*No shield*	*Thin*
LHe volume (Loss rate)	33 L (3 L/d)	62 (8 L/d)	70 L (6 L/d)	~ 70 L (10 L/d)	13 L (2.5 L/d)	8 L (2 L/d)	40 L (3.7 L/d)

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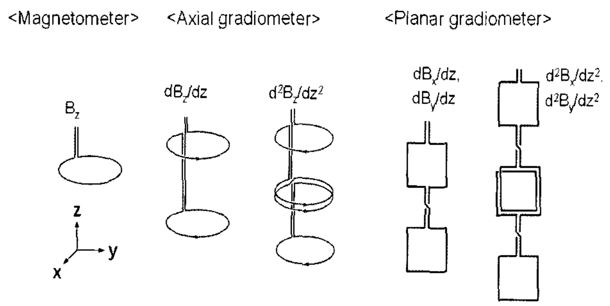


Fig. 1. Various types of pickup coils.

Fig. 2 shows several multichannel SQUID systems. Typically, magnetic field component or its derivatives normal to the chest surface, B_z, dB_z/dz or d^2B_z/dz^2 are measured using magnetometers, first-order axial gradiometer or second-order axial gradiometer, respectively. Planar gradiometers measuring off-diagonal derivatives, like dB_z/dx and dB_z/dy, or dB_x/dz and dB_y/dz are also used.

Wire-wound pickup coils have better mechanical reliability and stability again field trap than planar thin film coils. But, planar pickup coils have better intrinsic balancing due to the high accuracy of photolithography.

In real fabrication, however, stray pickup area or imbalance can be introduced due to the connection parts between the pickup coil and input coil of the SQUID. In order to shield this stray pickup area, superconducting shield tube or block is used which again affects the uniformity of the external fields and the SQUID sensor should be positioned far above the pickup coil to reduce the field distortion by the superconducting shield.

Measurement of magnetic field component normal to the chest surface shows a field pattern with two extrema for each current dipole. Thus, to collect the essential field distribution, we need a larger sensor coverage area than the tangential measurement.

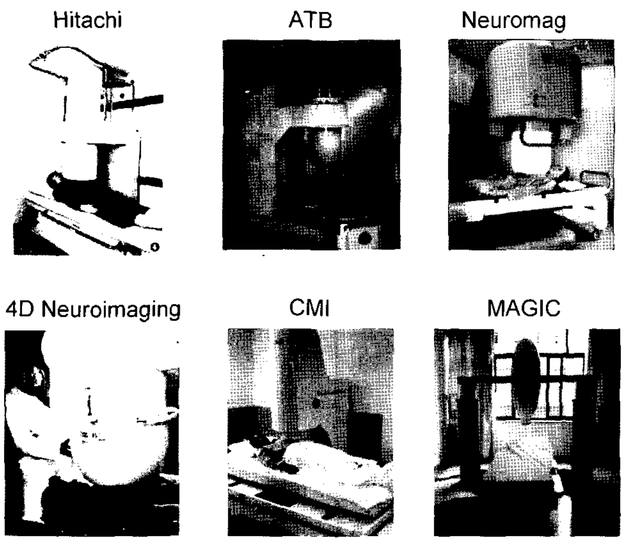


Fig. 2. Example of MCG systems developed by several organizations.

Tangential measurement has a field peak just above the current dipole, and we need a sensor coverage area smaller than the normal measurement to get the major field distribution. Thus, the dewar inner diameter can be made smaller than the normal measurement case, resulting in lower consumption of liquid He. Typically thin film pickup coils have a line width of about 1 mm, which is large enough to trap magnetic fluxes when the pickup coil is operated in an unshielded environment. Thus, unshielded operation favors the use of wire-wound pickup coils, unless the line width of planar pickup coil is narrow enough to increase the magnitude of the trap field.

In KRISS, we fabricated three types of pickup coil structures, magnetometer, planar gradiometer and axial wire-wound gradiometer, as shown in Fig. 3.

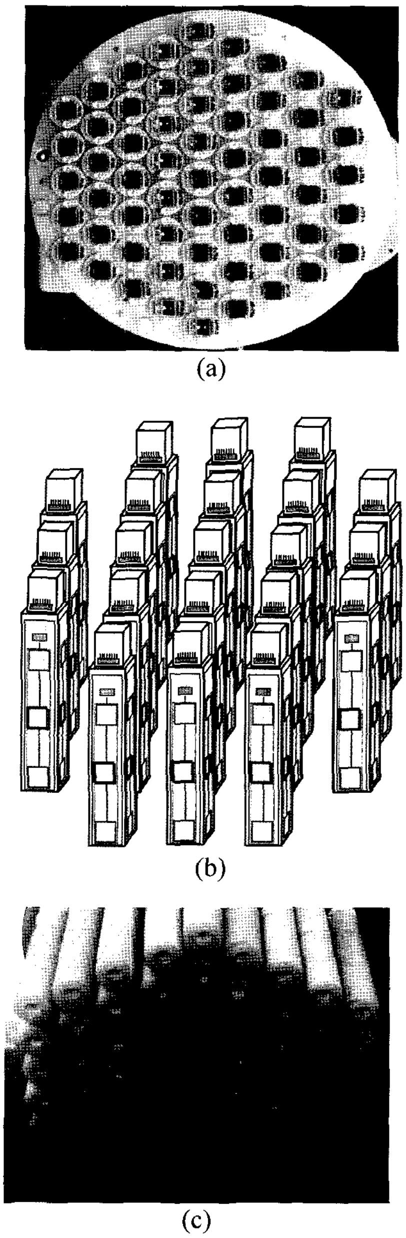


Fig. 3. Arrays of KRISS MCG systems. (a) 61-channel magnetometer, (b) 64-channel planar gradiometer and (c) 61-channel axial gradiometer.

2.2. KRISS MCG Systems

In a multichannel system, fabrication cost is also an important issue for the widespread distribution of the systems. The cost of an MCG system is determined by the components of SQUID, electronics, dewar, dewar support, patient bed, acquisition computer and software. In order to develop MCG systems providing good signal quality at economic combination, we optimized the component technology.

2.2.1. Second-generation SQUID

Conventional MCG systems use DC SQUIDs, which provides flux-to-voltage transfers of about 100 $\mu V/\Phi_0$ (Φ_0 is the flux quantum). If we amplify the output voltage of the DC SQUID by using room-temperature preamplifier a with input voltage noise of 1 nV/√Hz, the equivalent flux noise of the preamplifier becomes 10 $\mu\Phi_0/\sqrt{Hz}$. This flux noise is several times larger than the typical flux noise of the DC SQUIDs, meaning that the sensitivity of the SQUID is determined by the input noise of the preamplifier. In order to reduce the contribution of preamplifier input noise, additional efforts, like matching circuit at low-temperature or additional positive feedback scheme, etc, are needed.

In order to reduce the cost of electronics, we developed a novel SQUID scheme, double relaxation oscillation SQUID (DROS) which consists of a signal SQUID and a reference, shunted by a relaxation circuit of a resistor and an inductor. All the junctions in the DROS are hysteretic. If a dc current is biased through the signal SQUID and the reference junction, relaxation oscillations occur at a frequency of about 1 GHz. Among the relaxation oscillations, either signal SQUID or reference junction switches into voltage state depending on the relative magnitude of the critical current. If we amplify the voltage across the reference junction by using a preamplifier with gain bandwidth much lower than the relaxation oscillation frequency, time-averaged dc voltage can be measured.

In a dc bias current, the DROS functions as the comparator of two critical currents, the critical current of the signal SQUID and that of the reference junction. If the critical current of the signal SQUID is larger than that of the reference junction, there appears voltage across the reference junction. On the opposite case, no voltage signal is generated. If the flux to the signal SQUID is changed such that the two critical currents compete in magnitude, the output voltage changes abruptly, resulting in a large flux-to-voltage transfer coefficient [8].

Typical modulation voltages of DROS are in the range of 80~100 μV, and the flux-to-voltage transfers, $dV/d\Phi$, are about 1 mV/Φ_0, at around mid point of the modulation voltage. These flux-to-voltage transfers are 10 times larger than that of DC SQUIDs. By using DROS, the readout electronics can be made simpler than that of DC SQUIDs.

2.2.2. SQUID Pickup Coils

We fabricated 3 pickup coil structures, magnetometer, planar gradiometer and axial gradiometer. Magnetometer is an integrated pickup coil where SQUID and pickup coil are fabricated on the same wafer. The magnetometer has best sensitivity to deep sources, but has to be operated in the shielded room of type (a) or (b) in Fig. 4.

In planar gradiometers, first-order planar gradiometer with a baseline of 4 cm, and second-order planar gradiometer with a baseline of 5 cm were fabricated. The line width of the pickup coil is 1 mm.

In the axial gradiometers, we tried several types of gradiometers with different baselines, and optimized the baseline to 7 cm for operation in an economical shielded room while providing good signal-to-noise ratio. For the first-order axial gradiometer, a shield room with wall thickness of 8 cm can be used. And the second-order axial gradiometer can be operated inside a 1.2-cm thick shielded room for an economic and reliable operation.

2.2.3. SQUID Electronics and Control

Even though we use DROSs with large flux-to-voltage transfers, the output voltages of the SQUIDs are still low amplitude. To detect the SQUID voltage, we fabricated preamplifiers using common operational amplifiers LT1128 (Linear Technology). The input voltage noises of the preamplifiers were about 1.5 nV/√Hz at 100 Hz. For a typical flux-to-voltage transfer of 1 mV/Φ_0, the contribution of the preamplifier equivalent flux noise is 1.5 $\mu\Phi_0/\sqrt{Hz}$ at 100 Hz. This value is much smaller than the total flux noise of DROS planar gradiometers, 5.8 $\mu\Phi_0/\sqrt{Hz}$ at 100 Hz, which contains the intrinsic noise of the DROS, preamplifier noise, dewar thermal noise and residual magnetic noise of the shielded room. Represented as the flux noise power (square of the flux noise), the preamplifier contributes about 7 % to the total noise of the SQUID planar gradiometer, when the gradiometer system was operated inside a shielded room.

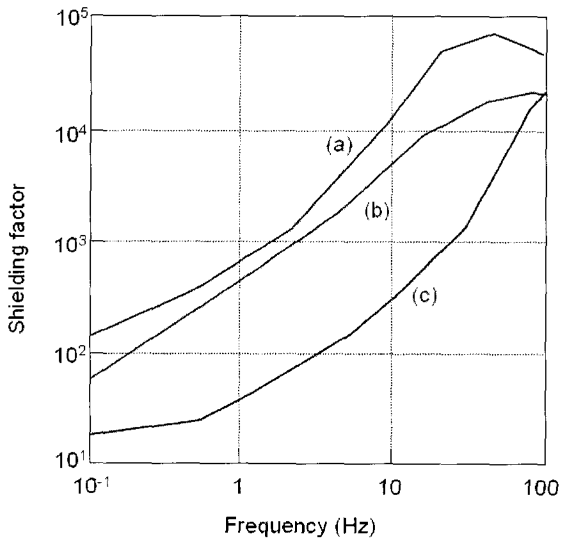


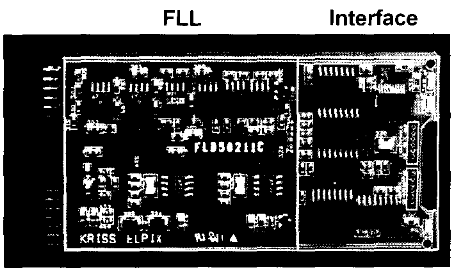
Fig. 4. Shielding factors as a function of frequency for 3 different shielded rooms. (a) Room with a wall thickness of 20 cm, (b) wall thickness of 8 cm and (c) wall thickness of 1.2 cm.

The 64-channel (or 61-channel) circuits consist of flux-locked loop (FLL) circuits and analog signal processing (ASP) circuits. 16 FLL printed circuit boards (PCBs) were assembled in parallel in one aluminum box, and 4 boxes for 64 the channels were installed on top of the dewar gantry.

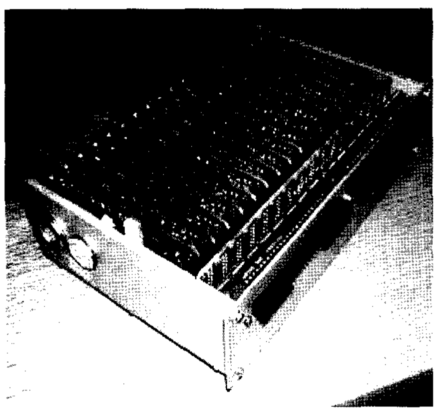
Fig. 5 shows the photographs of single FLL circuit board and 16-channel FLL box. The FLL outputs were passed through the ASP electronics, consisted of 16 PCBs and enter into the A/D card of the computer. Each ASP PCB has 4-channel ASP circuits and the ASP electronics were mounted in a single 19-inch sub-rack, outside of the shielded room. In order to control the FLL operations and ASP settings, digital pulses were used through a fiber-optic cable. The ASP circuits have high-pass filters (0.1 Hz), amplifiers (100 times), low-pass filters (100 Hz) and 60-Hz notch filters [9].

2.2.4. SQUID Sensor Insert

In the planar gradiometer array, the measuring components are tangential to the chest surface, dB_x/dz and dB_y/dz, where z-axis is normal to the chest surface. The insert consists of epoxy blocks for planar gradiometer, signal wires, a level meter, radiation shields (baffles), and a connector box, etc.



(a)



(b)

Fig. 5. Photographs of FLL circuits. (a) Single-channel FLL PCB circuit where analog FLL circuit and digital control circuit were mounted on a PCB and (b) FLL circuit box with 16 FLL PCBs were mounted.

The planar gradiometers at the tail part have 21 long rectangular holders and each holder has 2~4 planar gradiometers. Fig. 5 shows the arrangement of 64 planar gradiometers [10].

The standard distance between adjacent parallel gradiometers is 35 mm. Tangential gradiometers measuring off-diagonal components of the field gradient matrix has a magnetic field peak just above the current dipole when the pickup coil plane is arranged parallel to the dipole direction. Thus, it is possible to get the essential field distribution with a sensor coverage area smaller than the normal measurements. The senor coverage area of the 64-channel is 162 mm × 162 mm, which seems to be insufficient compared to the conventional MCG systems measuring the normal component. However, a simulation study showed that tangential measurements can localize current dipoles with a larger confidence region diameter than the normal measurement for the same confidence volume.

In the sensor arrays of magnetometer and axial gradiometer, hexagonal lattice structure was used for the sensor distribution as shown in Fig. 3(a) and 3(c). The sensor interval between neighboring channels is 26 mm, and the coverage of the sensor array is about 200 mm in diameter.

2.2.5. Liquid He Dewar

The multichannel systems were cooled by using nonmagnetic FRP dewars. The liquid He dewar for the 64-channel planar gradiometer system has an inner tail diameter of 192 mm, and the distance between the liquid helium and the room temperature is 20 mm. To increase the refill interval, main reservoir was installed. The main reservoir has a liquid volume of 34 L and the dewar tail has a volume of 6 L. When the 64-channel is in everyday operation, the average boil-off rate of the dewar is 3.6 L/d. Once the dewar is filled up, the liquid level drops to 15 L in a week. Though a liquid volume of 3 L is the minimum necessary volume to operate the 64 planar gradiometers, we refill the dewar once a week with a refill volume of 25 L.

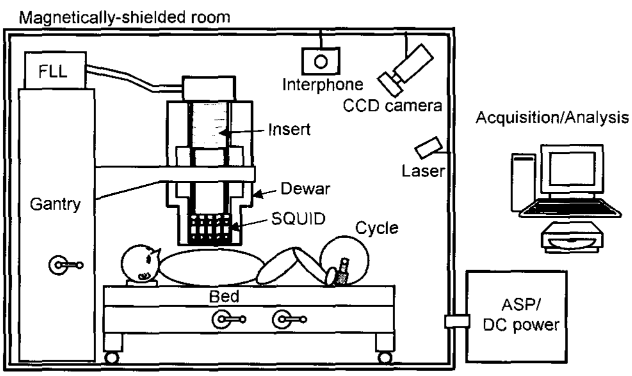


Fig. 6. Schematic block diagram of the MCG system.

2.2.6. Acquisition and Analysis Software

The control of SQUID sensors and readout electronics, and acquisition of MCG data were done by a computer through a 64-channel A/D card with a resolution of 16 bits. Automatic control of SQUID settings and ASP settings was done through a fiber optic cable. The control software has the functions of optimizing the operation conditions of SQUIDs and heating to remove trapped fluxes. The optimum condition of SQUID settings, such as bias current, voltage offset, flux bias, was determined by the criterion of minimizing the SQUID noise. In usual MCG measurements, a sampling rate of 1 kHz was used and measurement time was 30 s [11].

Fig. 7 shows an example of KRISS MCG system, where shielded room with a wall thickness of 8 cm was used for 64-channel planar gradiometer system. The total time needed to measure an MCG is about 5 minutes including the preparation time to remove the magnetic materials, like watch, mobile phone, etc.

After acquisition of MCG data, some digital signal processing was done, like baseline correction, digital filtering, optional averaging and field mapping.

From the measured magnetic field distributions, information on the myocardium currents can be calculated.

Fig. 8 shows an example of analysis software where mappings of magnetic field and current distribution were done at a specified time point.

Depending on the analysis process, parameter analysis or current localization can be done. In the case of parameter analysis, direction of current flow or temporal change of flow direction, etc. was compared between healthy controls and ischemic patients. To image the accessory current paths of arrhythmia, localization of current dipole was done and integrated on the heart anatomy of the patient.

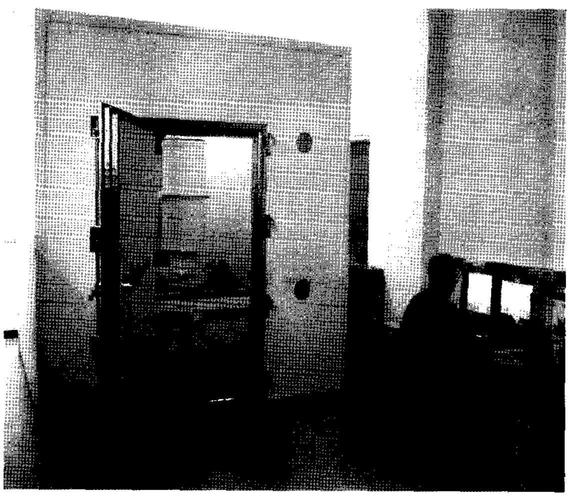


Fig. 7. A photograph of the KRISS MCG system.

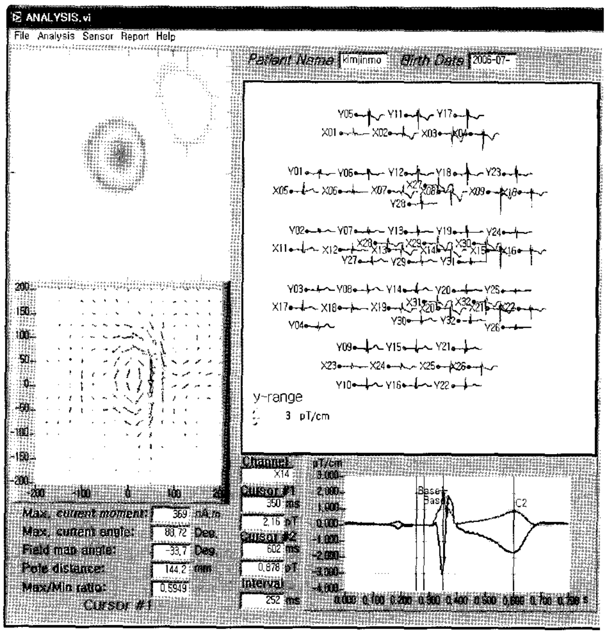


Fig. 8. Waveforms, field map and current arrow map of an MCG data.

3. CONCLUSIONS

By using multichannel SQUID systems, we can measure magnetic field distributions of human hearts. From these MCG data, functional diagnosis of heart disease can be done. Even though the field magnitude of MCG signals is large compared with brain magnetic signals, we need sensitive detectors for the accurate analysis of heart disease which contains tiny feature in the MCG waveforms.

Several multichannel MCG systems were developed, and installed at advanced heart centers. Though most of the MCG systems presently developed have performance good enough for measuring MCG data, there are some improvements to be done. The most important technical task remaining will be to make a multichannel system (say 60 channels) operating in a thin magnetically-shielded room while providing good-quality signals reliably. This may be done by the combination of a higher order gradiometer and signal processing algorithm.

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